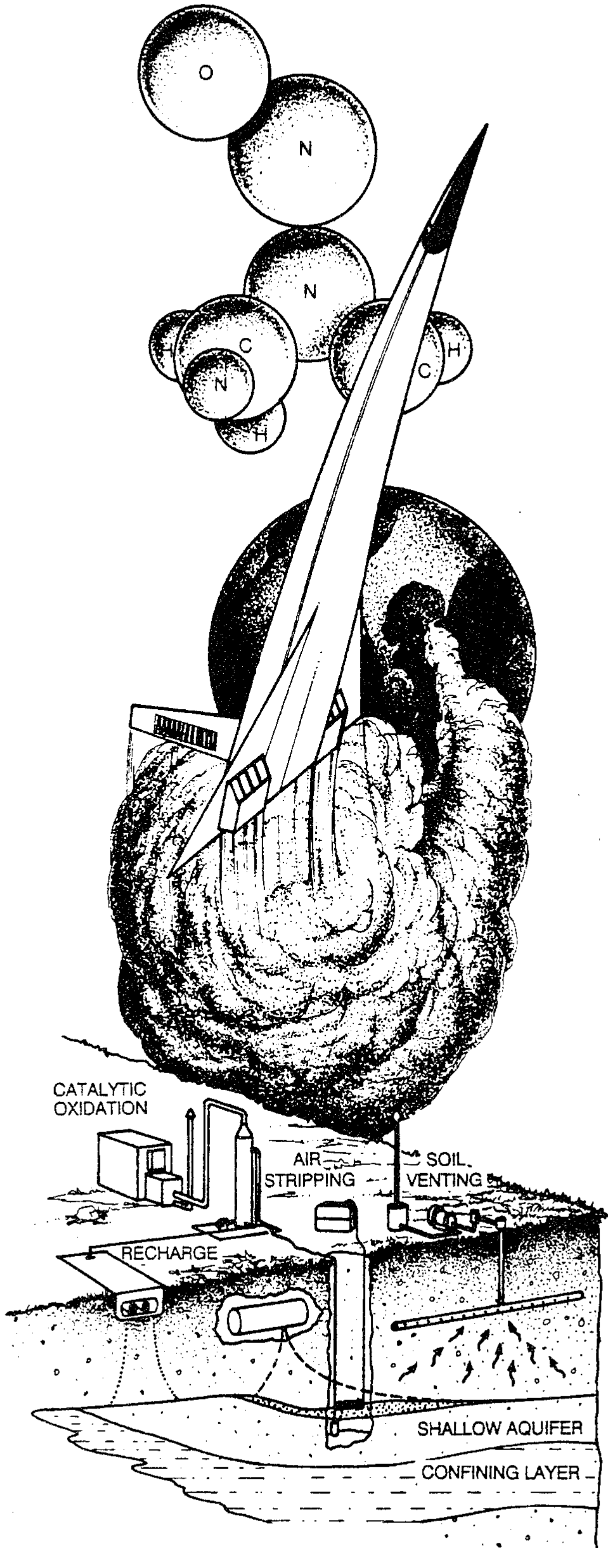


CEL-TR-92-57

EFFECTS OF STRUCTURES ON TOXIC VAPOR DISPERSION

L.L. SCHULMAN, S.R. HANNA,
R. BRITTER

SIGMA RESEARCH CORPORATION
196 BAKER AVENUE
CONCORD MA 01742

FEBRUARY 1996

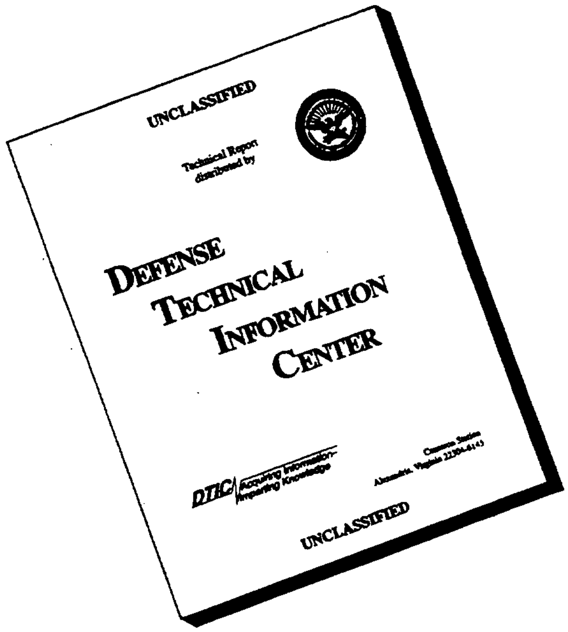
FINAL REPORT

MAY 1990 - NOVEMBER 1990

**APPROVED FOR PUBLIC RELEASE:
DISTRIBUTION UNLIMITED**

ENVIRONICS DIVISION
Air Force Civil Engineering Support Agency
Civil Engineering Laboratory
Tyndall Air Force Base, Florida 32403

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

NOTICE

PLEASE DO NOT REQUEST COPIES OF THIS REPORT FROM HQ AFCESA/RA (AIR FORCE CIVIL ENGINEERING SUPPORT AGENCY). ADDITIONAL COPIES MAY BE PURCHASED FROM:

NATIONAL TECHNICAL INFORMATION SERVICE
5285 PORT ROYAL ROAD
SPRINGFIELD, VIRGINIA 22161

FEDERAL GOVERNMENT AGENCIES AND THEIR CONTRACTORS REGISTERED WITH DEFENSE TECHNICAL INFORMATION CENTER SHOULD DIRECT REQUESTS FOR COPIES OF THIS REPORT TO:

DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22314

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1996

3. REPORT TYPE AND DATES COVERED
Final, 7 May 90 to 7 Nov 90

4. TITLE AND SUBTITLE
Effects of structures on Toxic Vapor Dispersion

5. FUNDING NUMBERS

6. AUTHOR(S)
L.L. Schulman, S.R. Hanna, R. Britter

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sigma Research Corporation
196 Baker Avenue
Concord MA 01742

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
HQ AFCESA/RAVS
Tyndall AFB FL 32403-5319

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
CEL-TR-92-57

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Same as report.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Currently available toxic vapor dispersion models at Air Force facilities do not adequately include the effects of structures on the rate of dispersion. Some relevant models and data sets are available in the literature as a result of research by other organizations. This literature was reviewed and an assessment made of the feasibility of producing a viable modeling system. It is found that increases in concentrations due to the confining effects of structures are significant relative to overall dispersion model uncertainty. A framework for a microcomputer-based modeling system is proposed that accounts for aerodynamic effects around one building or groups of structures, including downwash vapor and vapor trapping. Both neutrally-buoyant and dense gas cases are considered, and the model is constructed such that it is capable of a smooth transition to other dispersion models at downwind distances where the effects of the structures become significant.

14. SUBJECT TERMS
Toxic Hazards   Building Downwash
Disperson Modeling   Meteorology

15. NUMBER OF PAGES
107

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

(The reverse of this page is blank.)

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

EXECUTIVE SUMMARY

The ultimate product of this research will be a microcomputer-based modeling system that includes the effects of base-specific building structures in the dispersion of toxic chemical vapors. The modeling system should also be capable of interfacing with existing Gaussian puff or box models far downwind where the building effects become negligible.

None of the currently available toxic vapor dispersion models are capable of adequately treating the effects of structures, such as buildings, fences, and other obstacles. These models assume that transport and dispersion are dependent only on the wind speed, stability, and roughness in the surrounding open countryside. This neglect is generally justified by the argument that the presence of buildings will act only to decrease the concentrations because of increased mixing. However, there are several scenarios where the presence of buildings will increase the ground-level concentrations. For example, toxic gases released from the rupture of a pressurized storage tank located on the roof of a building may be drawn down into the aerodynamic wake of the building and cause injury to personnel attempting to escape from the building. Or, dense toxic gases may be trapped between the walls of adjacent structures and sheltered from ventilation by the normal wind flow.

The Phase I research had the objectives of reviewing the literature on the effects of structures on toxic vapor dispersion, assessing the feasibility of producing a viable quantitative model, determining whether the building effects are significant relative to overall model uncertainty, and recommending the framework for the model. Some of the questions that were addressed were:

(1) Do sufficient data and mathematical models exist for developing quantitative models for the effects of structures that can be used as subroutines in existing toxic vapor dispersion models?

(2) Are the expected changes in concentrations due to the effects of structures significant relative to overall model uncertainties?

(3) Do models and data exist for trapping of toxic clouds inside large open structures such as hangars?

(4) What is the relative accuracy of the subroutines for various source scenarios and various structure geometries?

(5) At what level of structure complexity do the models become inaccurate or data collection impractical?

The literature review found that in the case of passive gas releases on or near simple structures, adequate laboratory and field data and empirical/similarity models exist for several different source locations. However, a simple comprehensive model has not been assembled from these components. In the case of dense gas releases on or near simple structures, much data exist but relatively little analysis has been done and few general models have been proposed.

A key finding was that only a few specialized experiments have been carried out for complex confinement situations, such as street canyon networks or courtyards where ground level concentrations could be higher than in the absence of structures. Concentration increases of factors of 5 to 10 or more can occur in confinement scenarios. For many types of source scenarios the magnitudes of increases in concentrations due to the influence of obstacles are larger than the levels of uncertainty of model predictions.

The research indicated that the most feasible model approach would be a modular component framework using a matrix based on source location and receptor location relative to the structure. For example, a plume impingement model component would be incorporated for sources upwind of the structure for receptors on the building roof or face. A cavity release model component could be used for sources in the near-wake for receptors in the far-wake.

Higher-order turbulence closure models or numerical simulation models were found to be too complex for routine use and without assurance of greater accuracy.

The information (data and formulas) in the literature was used to develop a preliminary model that should form a basis for a concerted model development and evaluation effort in the future. A preliminary model code was written and tested that contains many of the desired components. This code can be the basis for further development in Phase II of the project.

As a result of this Phase I research program, the following recommendations are made:

(1) Existing dense gas data sets should be acquired and analyzed, with the goal of development of specific technical algorithms (e.g., formulas for the dilution of a dense gas cloud on either side of a fence).

(2) Plans should be made for the laboratory and field experiments necessary to fill in missing pieces in the comprehensive model, with emphasis on confinement scenarios.

(3) A comprehensive model should be put together for use on PC's. The model should apply to many types of obstacle configurations, source types and densities, and source-obstacle geometries.

(4) The new model should be evaluated with a wide variety of field and laboratory data and sensitivity tests should be carried out for the full range of possible input conditions.

(The reverse of this page is blank.)

PREFACE

This report was prepared by Sigma Research Corporation, 196 Baker Avenue, Concord, Massachusetts 01742, under the Small Business Innovative Research (SBIR) Phase I program, Contract Number F08635-90-C-0397, for the Air Force Civil Engineering Support Agency, Civil Engineering Laboratory (AFCESA/RAVS), Tyndall Air Force Base, Florida 32403.

This report summarizes work done between April 1990 and November 1990. AFCESA/RAVS project officer was Major Michael Moss.

Because this is an SBIR report, it is being published in the same format in which it was submitted.

This report has been reviewed by the Public Affairs (PA) Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

Mike Moss

MICHAEL T. MOSS, Maj, USAF
Chief, Environmental Compliance R&D

Neil J. Lamb

NEIL J. LAMB, Col, USAF, BSC
Chief, Environics Division

Frank P. Gallagher III

FRANK P. GALLAGHER III, Colonel, USAF
Director, Air Force Civil Engineering Laboratory

(The reverse of this page is blank.)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A	projected building frontal area
C_D	drag coefficient
C_m	maximum centerline concentration
C_o	initial concentration
C_p	predicted concentration
C_w	wake concentration
g'	buoyancy parameter (acceleration of gravity multiplied by fractional increase of cloud density over air density)
g_o'	buoyancy parameter at source (see g')
h	cloud depth
H	building height
H_c	height of roof recirculation cavity
H_R	height of near-wake recirculation cavity
H_s	stack height
L	building length
L_c	length of roof recirculation cavity
L_R	length of near-wake recirculation cavity
Q	source emission rate
q_o	volume flux
Q_o	initial cloud volume
r	"stretched string" distance
R	length scale
S	surface area enclosing near-wake region
t	time
t_r	time constant
u	wind speed
u_*	surface friction velocity
U	cloud speed
u_h	wind speed at building height
V	volume of near-wake region
W	building width
W_R	width of near-wake recirculation cavity
x	downwind distance
z_o	roughness length

LIST OF SYMBOLS
(Continued)

ΔH	plume rise
ρ_o	cloud density
ρ_a	air density
σ_y	horizontal dispersion coefficient
σ_z	vertical dispersion coefficient
τ_R	nondimensional residence time of particle in near-wake
$\propto$	constant

SECTION I

INTRODUCTION

Over the past ten years, large amounts of resources have been devoted by government agencies and private industries to the development and testing of computer models for toxic vapor dispersion. Nevertheless, none of these models is capable of adequately treating the effects of structures, such as buildings, fences, and other obstacles (Hanna and Drivas, 1987). The other models assume that transport and dispersion are dependent only on the wind speed, stability, and roughness in the surrounding open countryside. This neglect is generally justified by the argument that the presence of buildings will act only to decrease the concentrations because of increased mixing. However, there are several scenarios where the presence of buildings will increase the ground-level concentrations. For example, toxic gases released from the rupture of a pressurized storage tank located on the roof of a building may be drawn down into the aerodynamic wake of the building and cause injury to personnel attempting to escape from the building. Or, dense toxic gases may be trapped between the walls of adjacent structures and sheltered from ventilation by the normal wind flow.

The U.S. Air Force, among others, has increased emphasis on calculating "toxic corridors" due to potential releases of toxic chemicals. The models used to calculate these corridors should be as comprehensive and accurate as possible, including all significant physical phenomena. This research investigates the importance of including the effects of structures in toxic vapor dispersion models, and suggests preliminary approaches to quantifying these effects in models.

The Phase I research is intended to determine the feasibility of the research program, which then may be carried out in a comprehensive fashion in Phase II. In this case, the Phase I research has the objectives of reviewing the literature on the effects of structures on toxic vapor dispersion, assessing the feasibility of producing a viable quantitative model, and determining whether the building effects are significant relative to overall model uncertainty. The literature survey has followed a framework

defined by a matrix based on source location and receptor location relative to the structure:

		Receptor Location		
		On Face of Structure	In Wake or Cavity Of Structure	Downwind of Wake of Structure
Source Location	Upwind of Structure			
	On Structure			
	Downwind of Structure			

In addition, the literature has been stratified into dense gases and passive gases, and into puff and continuous plume sources. The research has attempted to answer the following questions:

- Do sufficient data and mathematical models exist for developing quantitative models for the effects of structures that can be used as subroutines in existing toxic vapor dispersion models?

- Are the expected changes in concentrations due to the effects of structures significant relative to overall model uncertainties?

- Do models and data exist for trapping of toxic clouds inside large open structures such as hangars?

- What is the relative accuracy of the subroutines for various source scenarios and various structure geometries?

- At what level of structure complexity do the models become inaccurate or data collection impractical?

The six-month study conducted as Phase I of this research plan has resulted in a set of conclusions and recommendations concerning the feasibility of the development of methods to quantitatively evaluate the

effects of large structures on the transport and dispersion of toxic vapors. The following sections present the results of the work tasks and lists the recommendations.

SECTION II

LITERATURE REVIEW

A. PASSIVE RELEASES

There is a very extensive set of literature concerning passive releases. These papers include both field and laboratory data and many models with varying levels of complexity that have been developed to explain the data. General reviews of available data and models have been prepared by Hosker (1980, 1982, 1985), Meroney (1982), and Fackrell (1984). Appendix A contains a list of references for passive releases and a detailed summary of a few selected references.

For passive releases, the literature generally considers flow near simple, isolated buildings. Even this seemingly uncomplicated problem has been the subject of hundreds of studies. Indeed, Leonardo da Vinci (c. 1505, see Figure 1) pondered the complexities of flow in the lee of obstacles almost 500 years ago. Studies of passive flow and source dispersion near isolated structures has traditionally been divided into four regions: upwind of the structure (about 2 building heights upwind), on the roof or face of the structure, in the cavity or near-wake of the structure (up to 2-3 building heights downwind), and in the far wake of the structure (from 3-10 building heights downwind). Figure 2 illustrates the complex flow patterns near an isolated structure.

A far less extensive set of literature is concerned with the effect of clusters of buildings. Most of these studies have been conducted in the laboratory and many have been conducted to provide information on pedestrian-level winds for architectural purposes or dispersion of automobile exhausts in urban street canyons. Some industrial analyses have been conducted (Hatcher, Meroney, Peterka, and Kothari, 1978, for example), and these references have also been included in Appendix A. However, there is sufficient remaining uncertainty in modeling the effects of shape and wind orientation for simple, isolated buildings that the bulk of the research is still directed in that area.

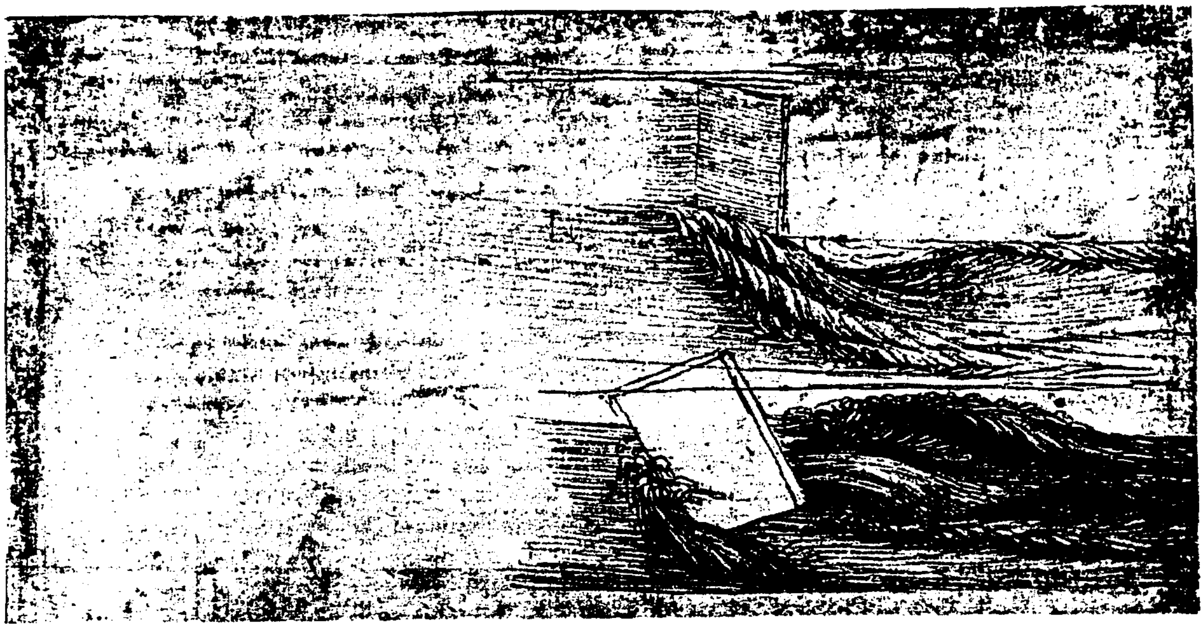


Figure 1. *Studies of Leonardo da Vinci* (c. 1505). These drawings show the vortices that form in the lee of obstacles or when water is poured into a reservoir.

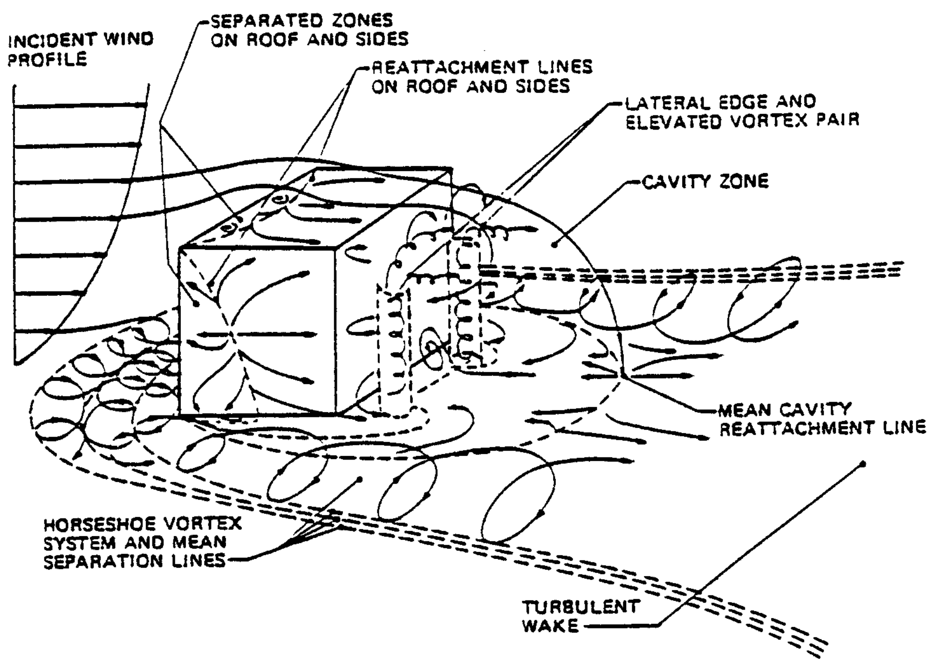


Figure 2. Schematic diagram of flow near a sharp-edged three-dimensional building in a deep boundary layer (from Hanna, Briggs, and Hosker, 1982).

Aside from the general review papers, the most commonly cited references for the various regions of passive releases are:

Isolated structures

Upwind - Wilson and Netterville (1978); Britter, Hunt and Puttock (1976)

On Building - Wilson (1979, 1982 (with Britter), 1983, 1985 and 1987 (with Chui)); Halitsky (1965)

Near Wake - Wilson and Britter (1982); Fackrell (1984); Briggs (1973); Turfus (1988); Vincent (1978)

Far Wake - Briggs (1973); Huber (1976 (with Snyder), 1988, 1989); Robins and Castro (1977); Schulman and Hanna (1986)

Building Clusters

- Wise (1971); Britter and Hunt (1979); Penwarden and Wise (1975); Hatcher, Meroney, Peterka and Kothari (1978); Hosker (1987); Halitsky (1977); Logan and Barber (1980); Yamartino and Wiegand (1986).

B. DENSE GASES

The set of literature for dense gases is much less extensive than for passive releases. Although there has been a wealth of data collected over the past five years from both laboratory and field studies, there have been few papers interpreting the data. The most complete review has been conducted by Brighton (1989). A list of references on dense gas releases is contained in Appendix A, as well as a summary of selected references. Because this literature is not as well reviewed, a more thorough discussion than for passive releases is presented in this section.

The dense gas literature is often divided, as for passive releases, into isolated structures and clusters of structures. Two other groups, however, are also considered in the dense gas literature. These are confining structures which reduce the surface area of the cloud available for dilution by the velocity field, and sheltering structures which reduce the velocity field and thus the effect of wind dilution.

1. Isolated Structures

There are generally three source release situations for isolated structures that are considered in the dense gas literature. These are a release well upwind of the building, at the upwind face of the building, and in the near or far wake of the building.

a. Release Well Upwind of the Building

Laboratory experiments by Krogstad and Pettersen (1986) and the analysis by Brighton and Prince (1987) of the instantaneous release Phase II Thorney Island field trials support the hypothesis that building surface concentrations will be equal to or less than the maximum cloud (plume or puff) concentration in the absence of the building. This results from the development of a "horse-shoe" vortex structure surrounding the building bringing air from aloft down into the gas cloud and diluting the cloud near the building. This diluting effect was observed to be greater the larger the ratio of the building size to the plume depth. Wake generated turbulence will also act to reduce concentrations in the lee.

Downwind of the building Kothari (1981) found that a plume tends to have its maximum concentration off the centerline downwind of the building. This is caused by increased turbulence and dilution in the wake, the presence of horse-shoe vortices with longitudinal axes, and the lateral deflection of the plume by the structure.

The maximum concentration (at a lateral cross-section) is reduced by the presence of the buildings. The concentration reductions, summarized by Brighton (1989) show that the reductions are surprisingly

slight, the more stable plumes show less reduction, and in some cases the reduction increases with distance downstream from the building.

These observations suggest that the diluting ability of the turbulence generated in the building lee may be severely limited in the case of dense gases by the tendency of the dense cloud to remain removed from the immediate lee of the building. Thus, both the typically large widths of the dense plumes and the tendency of the plumes to bifurcate around the wake will lead to a reduced building influence when compared to passive releases.

Similar passive plumes could all be entrained into the building wake, diluted there and then released; very approximate calculations would suggest dilutions nearly an order of magnitude larger than observed for the dense gas cases. Note here that we are comparing concentrations in the immediate lee for passive releases and concentrations well off the centerline for strongly bifurcated dense releases.

b. Release Just Upwind of the Building

Experiments by Kothari, Meroney and Neff (1981), Krogstad and Pettersen (1986), and by Duijm (1987) all show the tendency for a wide bifurcated plume although this may be partly due to the large lateral extent of the plume at the source position. The Kothari et al. (1981) work shows concentration reductions to about 60% of the no-structure case; a decrease which is persistent out to 10 structure heights downwind.

c. Release Downwind of the Building

Kothari, Meroney and Neff (1981) also investigated this case. Their results do not show the bifurcated structure seen with the structure downstream of the release, except when the structure is very close to or co-incident with the source. The observations show reductions in concentration due to the structure, the reductions being larger for the less stable plume. The upwind structure produces greater dilution than an equivalently spaced downwind structure. This may result from more of the plume being within the structure wake in the former case.

Britter (1989) performed a generic study of releases into the wake of a structure normal to the wind. For less stable plumes, the experimental results suggested that concentrations were similar to those estimated from passive dispersion. For more dense releases the plume spreads outside the structure cavity and tends to stratify within the cavity.

As a summary of the relevant references for isolated buildings:

Well Upwind	- Krogstad and Pettersen (1988); Kothari, Meroney and Neff (1981); Reithmuller (1986); Dirkmaat (1981); McQuaid and Roebuck (1985); and Brighton and Prince (1987).
Just Upwind Source	- Kothari, Meroney and Neff (1981); and Duijm (1987).
Downwind Source	- Britter (1989); Kothari, Meroney and Neff (1981); Brighton & Prince (1987) or McQuaid and Roebuck (1985).

2. Confining Structures

Not surprisingly there have been several laboratory and field studies of structures that intentionally or inadvertently confine the release. These structures also frequently mitigate the effect of the release through enhanced dilution after escape from confinement.

Kothari and Meroney (1982) performed wind tunnel tests and simulated continuous LNG plume releases. They considered the influence of enclosing fences and vortex generators. They found that vortex generators and fences enhanced plume dilution with the solid fence being preferable. Plume dilution was increased with higher fences, smaller source flow rates and placing the fences as close as possible to the source. When the fence was present lower wind speeds gave larger concentrations. However, for the unobstructed case, the higher wind speed gave the maximum concentration.

A further wind tunnel study by Petersen and Diener (1990) also addressed the influence of various mitigating devices on dense gas releases. They concluded that two dimensional vapor fences reduced near field concentrations, but the concentrations approached the no-fence case in the far-field. In addition, two-dimensional vapor fences did not appear to increase significantly cloud arrival times.

Comparable full scale tests were carried out in the Thorney Island Phase 3 studies (see Brighton, 1989) using a rectangular fence 54 m x 26 m x 2.44 m high. The general conclusions were broadly similar to the wind tunnel studies. The fence acted as a substantial diluting agent for material escaping over the fence and acted to confine material within the fence thereby reducing the effective source flow.

As part of the Phase II Thorney Island field study, experiments were performed with instantaneous releases within a semi-circular, solid fence 5 m high. The analysis of these experiments is summarized in Brighton and Prince (1987) and Brighton (1989). Wind tunnel simulations of these experiments have been undertaken by Davies and Singh (1985), Knudsen and Krogstad (1987), and Konig (1987). The results show that under strong winds the cloud was carried over the structure suffering strong dilution in the lee. At lower wind speeds the phenomenon of blocking was evident with the material upwind of the structure being slowly eroded and carried over the structure.

Britter (1989) provided data from two relevant generic studies. The first considered the interaction of a two-dimensional fence normal to the flow. Two physical phenomena of some importance were observed. For weakly stable plumes and low fence heights the plume was swept over the fence whereas very stable plumes could be "blocked" by the fence and held-up on the upwind side. Released material would accumulate on the upstream side and increase in depth. This pooling of material developed a sloped interface and increased in depth until it lapped over the fence or reached regions of sufficiently high velocity to cause mixing and thus sweep material over the fence. Eventually the flow over the fence would increase to equal the release rate. Prior to this far smaller fluxes removed from the pool surface were carried across the fence.

The second observation was that material that did cross the fence was well mixed throughout the highly turbulent wake. The mixing process was as if the release was passive and simple correlations proved suitable to describe the near-wake coNcentrations. The plume develops a more dense-gas nature further downstream where the wake turbulence has decreased.

An extension of this study was to consider a dense-gas plume from an area source interacting with a two-dimensional fence. In this case the plume widened considerably upstream of the fence and then was swept over the fence in a manner similar to the two-dimensional release study. This plume widening and the subsequent "passive" mixing in the lee produced very dramatic reductions in plume concentrations (up to a factor of 34 in the experiments cited).

Rottman et al. (1985) noted that the leading edge of a gravity current interacting with a solid fence will cause material to be "splashed" to a height of about twice the gravity current height. Thus although a steady flow might be blocked by a fence the transient interaction may lead to some material crossing the fence.

Marotzke (1988), following Konig and Schatzman (1986) and Konig (1987), presents results for several confining structure types. The structure types have been selected in part as cases that might lead to increases in hazard distances. These included single walls parallel to the flow which did lead to substantial concentration <u>increases</u> for both instantaneous and continuous releases.

A semi-circular wall surrounding the source produced reductions in ground level concentrations. The earlier work of Konig also considered a rectangular ditch normal to the flow. For various instantaneous and continuous sources the ditch always acted as a diluting structure with some confining effect as the cloud traveled a little way along the ditch. Further studies on a street canyon at 45° to the flow and an intersecting street canyon are discussed under sheltering structures.

Although not really a confining structure, the porous fence has enough similarities with the solid fence to justify its inclusion here. Porous fences may be found, in practice, as regions or belts of trees, as pipe racks, or some other porous array. These are characterized by regions in which the typical size of any solid element is far smaller than the region itself. Brighton (1989) argues that such regions might be treated as a continuum using representative area as volume average quantities, e.g., porosity or volume fraction (kinematic quantities) or drag coefficient per unit volume (a dynamic quantity). Such an approach is not novel and has been used, for example, in considering flame acceleration through complex structures.

Brighton also suggests two generic cases; a porous layer on the ground of height H with specified properties and a transverse barrier of height H and downstream length L with specified properties. It is the latter which we consider to be a fence.

Kothari, Meroney and Neff (1981) modeled a treeline with porous material. Little information is presented concerning the representativeness of this modeling but the material had a porosity of 30%. The tests were done with other isolated structures present so it is difficult to determine the influence of the simulated fence alone. In two cases (Runs 21 and 22) these effects may be separated and it is apparent that the fence produces only a slight reduction in concentration in the immediate lee and quite substantial reduction (a factor of 4) further downwind. There is slight plume broadening due to the fence similar to that seen with solid fences.

Jensen (1984) performed field experiments with a porous fence. However the parameter range was such that little effect would have been anticipated even for a solid fence. He found insignificant influence.

Two Thorney Island Phase II experiments used a semi-circular porous fence. Two fence porosities were tested; one producing a velocity reduction in the fence lee to 0.4-0.5 of that upstream; the other a reduction 0 to 0.2 of that upstream. Significant fence effects were only found for the less porous fence. Brighton (1989) summarizes the analysis of these cases. In the

near field the porous barrier has little effect but the concentration was reduced by a factor of two or so downwind. The altered wind field also affected the advection velocity of the cloud and led to some persistence of the released material.

Similar but substantially larger effects were observed by Petersen and Diener (1990) from their models of a heavily and moderately obstructed process units. A small dilution in the immediate lee is followed by larger dilutions downstream. Of course virtually undiluted material will be able to travel through the porous structure and then suffer dilution further downwind. Porous structures generally do not have a recirculating cavity in their immediate lee.

A further usable observation is that, as with all obstructions, the effect of the porous fence decreases in the very far field as the diluting process reduces back to one determined by the ambient turbulence.

Rottman et al. (1985) studied a dense flow through a porous fence (as a finite array of structures) but with no ambient flow. Little plume dilution was observed though some reflection and a height decrease through the array was evident. The decrease is consistent with hydraulic flow with a distributed drag.

As a summary of the relevant references for confining structures:

Source Upwind of Fence - McQuaid and Roebuck (1985); Brighton and Prince (1987); Knudsen & Krogstad (1987); Davies & Singh (1985); Konig (1987); Reithmuller (1986); Britter and Snyder (1987); White (1987); Rottman et al. (1987); Marotzke (1988); Britter (1989); Jindal (1989); Kim, Brandt & White (1990); Petersen and Diener (1990).

Source Within a Fence - Kothari and Meroney (1981); Konig (1987) and Marotzke (1988); Brighton (1989); Petersen and Diener (1990); Briggs, Thompson & Snyder (1990).

3. Sheltering Structures

This category refers more to a particular group of scenarios rather than structure types and it contains situations where the mean velocity is reduced causing the influence of the negative buoyancy of the cloud to become more apparent. In all cases there will be a simultaneous increase in the turbulence levels. The net effect on surface concentration will depend upon the relative importance of the decreased mean and increased turbulent velocities.

a. Upwind sheltering

Britter and Snyder (1987) found that there was a small increase in concentration near the base of a ramp arising from an upwind source. This increase can be traced back to the reduced near-surface mean velocity and consequent reduced turbulent mixing at that position. A similar slight effect is anticipated for steeper slopes and three-dimensional structures. However, in the latter case, the development of a "horse-shoe vortex" will reduce the surface concentrations.

b. Downwind sheltering

Immediately downwind of a structure the mean velocity is reduced and the turbulence levels increased. The reduction in mean velocity can cause a dense jet to return to the surface far closer to the surface and with large concentrations. For this to be relevant the dense jet would need to remain in the near-wake region and this may be unlikely for a high-momentum release.

A surface release of dense fluid will travel upwind against an ambient flow. This generally upwind flow will be very marked within the low velocity region in the near-wake, leading to the cloud impinging on the downstream face of the structure.

c. Confinement sheltering

The reduced mean velocities within a confining fence will tend to cause the release to spread over the surface of the confined region with the increased turbulence scouring the spreading pool. This scenario has been discussed earlier under confining structures.

d. Partial confinement/sheltering

Within this category is included the general influence of obstacle arrays wherein the cloud is shallower or comparable to the depth of the structures. Generally the view of these problems (see Petersen (1987)) is that the influence of the structures is to act as an increased roughness and substantially reduce the surface concentrations. Also within this category we include the release in a complex of street canyons which is partially confining <u>and</u> sheltering.

Both these effects lead to increased ground level concentrations. It is of interest to consider some examples of this to see whether the sheltering and partial confinement is dominant over the influence of the accompanying increased turbulence. Note that the previously considered single or multiple walls parallel to the flow produce a confinement effect but no sheltering.

Reithmuller (1986) generally found the street-like structures led to reductions in surface concentrations.

Konig (1987) considered a release at the intersection of two street canyons with the wind parallel to one of the canyons. For instantaneous and continuous releases substantial dilution is provided by the ambient flow and the intersection. In the absence of an ambient flow the concentration development is constant with a simple flow-equipartition argument.

4. Building Clusters

A description of relevant experiments from Fannelap and Zumsteg (1986), Bradley and Carpenter (1983), Guldemond (1986), and Reithmuller (1986) was made by Brighton (1989).

Further data is available in Dirkmaat (1981), Peterson and Ratcliff (1989) and Petersen (1989); the latter two references providing data on a well-documented study.

Data from a generic study of the influence of structure arrays is provided in Melia and Britter (1990).

These studies show that with appropriate care an industrial site can be modeled as an equivalent uniform roughness. The ambient velocity profile should acknowledge the importance of displacement thickness.

SECTION III

SCENARIOS CAUSING INCREASED CONCENTRATIONS AND COMPARISONS WITH OVERALL MODEL UNCERTAINTY

Nearly all of the available dense gas dispersion models ignore the effects of structures, and justify this assumption with the argument that the structures cause increased dilution and hence reduced concentrations. In contrast, many of the available passive gas dispersion models account for the effects of structures, because of the practical problems associated with releases from vents on buildings, and because buildings are known to cause downwash of short stack plumes.

The literature review presented in Sections I and II of this report demonstrates that there are several scenarios in which the presence of structures causes significant increases in concentrations resulting from dense gas releases. During the past few years, many laboratory and field studies have been carried out in order to investigate this phenomenon. In this section these scenarios will be described and the magnitude of the resulting increases in concentration compared to the magnitude of model uncertainty.

A. SCENARIOS IN WHICH STRUCTURES CAUSE INCREASED CONCENTRATIONS

It is obvious that if one builds a high wall completely around an area where a toxic chemical is stored, the resulting maximum concentrations inside the wall in the event of an accidental release will be much greater than if the wall were not present. Outside the wall, however, the concentrations will be less due to the increased dilution and time delays imposed by the wall.

There are not many field or laboratory studies in which these confining scenarios are emphasized. Two investigators (Konig, 1987, and Marotske, 1988) observed factor of five increases in concentration within street canyons. However, Petersen and Diener (1990) restricted their discussions to observed concentrations downwind of a fence, because of the potential use of the fence to "mitigate" maximum concentrations at the plant boundary.

Some specific examples of scenarios leading to increased concentrations are given in Figures 3 through 10. All of these scenarios are marked by one or more of the following effects:

1) Reduction in velocity
2) Confinement due to physical boundaries
3) Alteration of cloud trajectory

As mentioned earlier, effects (1) and (3) are often countered by increased turbulence, which acts to enhance the dilution of the cloud (see Figures 7, 8, 9, and 10). Consequently, effect (2), i.e., confinement (see Figures 3, 4, 5, and 6), has the most potential for increasing concentrations. One possible mathematical model for this phenomenon would involve a box model with some assumption regarding detrainment. For the case of "ultimate confinement," i.e., a completely enclosed room which exchanges air with its environment once every T_e hours, a simple exponential formula can be applied where the concentration at any time, t, is proportional to exp $(-t/T_e)$. The reader can envision much more complex examples of confinement which are amenable to study only by physical models.

B. OVERVIEW OF UNCERTAINTIES IN TOXIC GAS DISPERSION MODELS

The past decade has seen a growth in interest concerning the uncertainty in air pollution dispersion models (Fox 1984, Carson 1986, Benarie 1987, Venkatram 1988). The old rule of thumb was that dispersion models carried a "factor of two" uncertainty. Recent model development programs have had the objective of significantly reducing this uncertainty, but researchers have discovered that there is a large amount of irreducible uncertainty due to stochastic processes in the atmosphere and due to the limitations of measurements. We have recently been involved in a broad range of air quality model development and evaluation exercises, involving the use of data from about 20 independent full-scale field experiments. The sources in most experiments are continuous point sources within the lowest 100 m of the boundary layer. An overview of the results of each of these studies is given below.

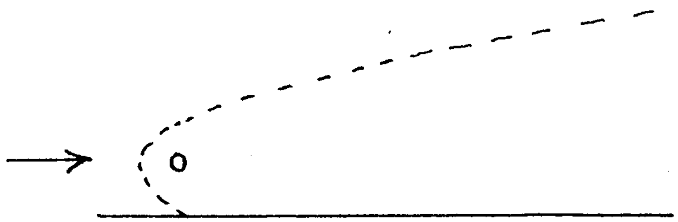


Figure 3. Cloud confined by a single fence. The source is marked by a small "o."

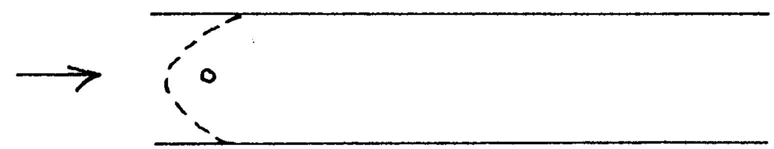


Figure 4. Cloud confined by two fences (e.g., a street canyon). The source is marked by a small "o."

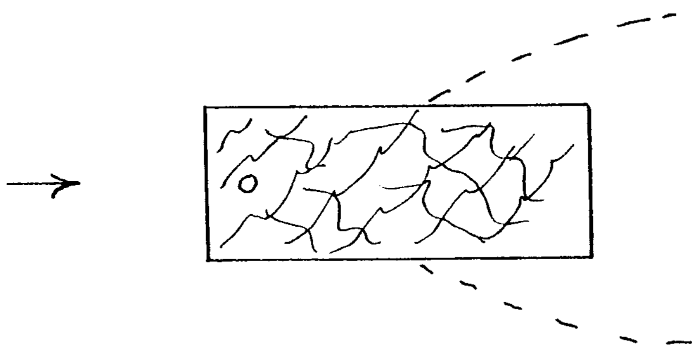


Figure 5. Cloud completely confined by four fences (e.g., a courtyard). The source is marked by a small "o."

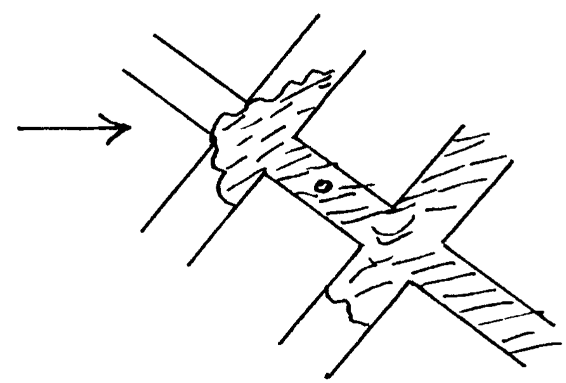


Figure 6. Sheltering effects and partial confinement in a street canyon system.

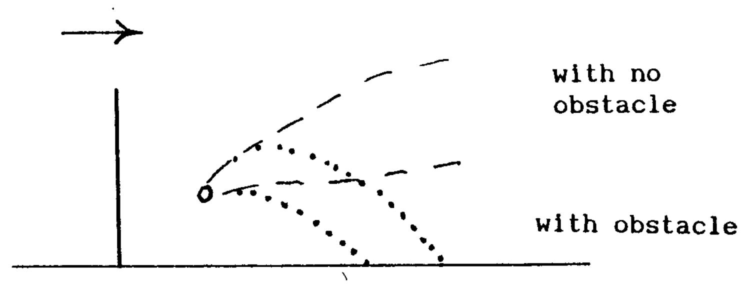


Figure 7. Sheltering effects leading to changed plume trajectory. The net effect of the structure will depend on whether the reduction in mean velocity is outweighed by the increased (dilution due to) turbulence.

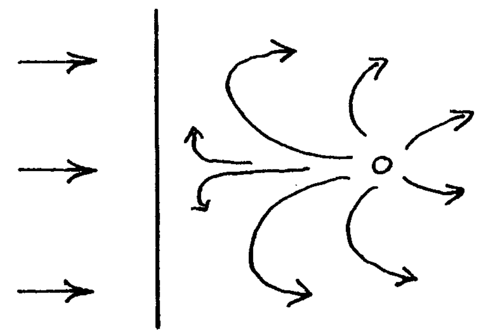


Figure 8. Sheltering effects leading to upwind flow. The source is marked by a small "o."

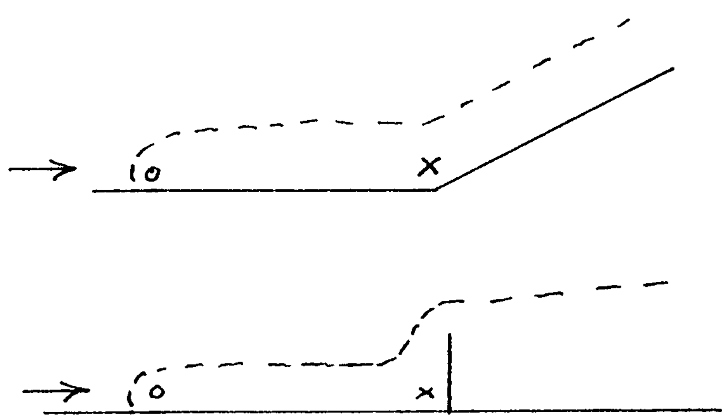


Figure 9. Possible slight increases due to reduced mean velocity (i.e., sheltering) in the neighborhood of slopes and fences. The source is marked by a small "o."

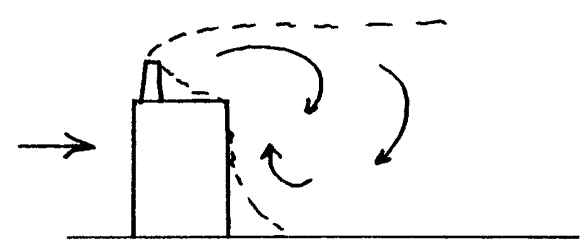


Figure 10. Structure effects such as building downwash that are also encountered when the release is passive.

Prairie Grass Experiment: The 1956 Prairie Grass experiment resulted in a comprehensive dataset containing 44 separate runs, where SO_2 was released from a near-surface continuous point source over flat terrain, and detailed supporting meteorological data were taken. Concentrations were measured on five downwind monitoring arcs (50 m to 800 m). This dataset represents the optimum research-grade field experiment for which data uncertainties are minimized. An optimized model is found to explain about 93% of the variance in the observations, and the rmse or scatter of the predicted C/Q about the best-fit line at any observed C/Q averages about 20 to 30%.

Overwater Tracer Experiments: The Offshore and Coastal Dispersion (OCD) model was developed to estimate the on-shore impact of pollutants released from offshore oil platforms. The OCD model was evaluated using 101 individual runs from field experiments at four separate locations (DiCristofaro et al. 1990). Tracer gas was released at elevations of 10 to 20 m above the water, at distances 1 to 15 km from the shoreline, and concentrations were observed by lines of monitors at the shoreline. The results of the model evaluation exercise at the four sites demonstrate that the ratios of the means, $\overline{C}_p/\overline{C}_o$, range from 0.65 (i.e., a 35% underprediction) to 2.13 (i.e., a 113% overprediction) from experiment to experiment, with a median of 1.07. The relative rmse ranges from 0.42 to 1.17 (i.e., 42 to 117%) from site to site. It is interesting that the model will underpredict at one site and overpredict at another, suggesting that model biases obtained at a single site should not be extrapolated to other sites, and that one should not jump to conclusions if data from only one or two sites are analyzed.

Experiments with Stack Plumes in Urban Areas: An Urban Hybrid Plume Dispersion Model (HPDM-Urban) was developed and evaluated using about 80 hours of tracer data from the buoyant plume from an 83 m power plant stack in Indianapolis. Maximum predicted and observed concentrations on downwind arcs ranging from 0.25 to 12 km were considered for a wide range of stability conditions (Hanna and Chang 1990). It was found that the ratio of the means, $\overline{C}_p/\overline{C}_o$, equaled about 1.1 (i.e., a 10% overprediction), and the relative rmse was calculated to be about 0.60 (i.e., 60%).

Dense Gas Field Experiments: As part of an ongoing project, 10 toxic gas models (none of which account for the effects of obstacles) are being evaluated with data from ten full-scale dense gas field experiments. A thorough description of a preliminary version of this model evaluation exercise is given by Hanna et al. (1990). It is found that the best model has a typical relative mean bias of about $\pm$ 30% and a typical relative rmse of about 70%.

Dense Gas Laboratory Experiments: Britter and McQuaid (1988) have plotted large quantities of experimental data from dozens of independent studies of hazardous gas dispersion in order to derive a set of nomograms for the downwind length of toxic corridors defined by specific dilution ratios. The dilution ratios are given in terms of the ratios of the maximum plume centerline concentration, C_m, to the initial concentration, C_o. Downwind distances are scaled by $Q_o^{1/3}$ for instantaneous releases, and $(q_o/u)^{1/2}$ for continuous releases, where Q_o is the initial volume of the instantaneous release, q_o is the volume flux (in volume per unit time) of the continuous release, and u is a representative wind speed. The nomograms give the best-fit scaled distances to several representative C_m/C_o values as a function of an initial Richardson number or stability parameter, defined as $g_o'Q_o^{1/3}/u^2$ for instantaneous sources and $(g_o')^2q_o/u^5$ for continuous sources, where $g_o' = g(\rho_o - \rho_a)/\rho_a$ is the buoyancy parameter. In this definition, g is the acceleration of gravity (9.8 m/s^2) and ρ_o and ρ_a are the initial cloud density and the air density, respectively.

We have analyzed the data in Britter and McQuaid's (1988) graphs in order to estimate the magnitude of the relative bias and rmse about the best-fit curves. Figure 11 contains some of the diagrams from Britter and McQuaid (1988) for cases of continuous dense gas releases in the laboratory, illustrating the large amount of scatter in this particular data set.

As a result of the analysis of the entire set of data, it is found that the typical uncertainty with respect to the best-fit curve within any given data set is about $\pm$ 10 to 20% of the mean, with maximum uncertainties of about $\pm$ 70% for some data sets. Furthermore, it is found that the mean of any given data set could differ by $\pm$ 50% from the mean of other similar data sets.

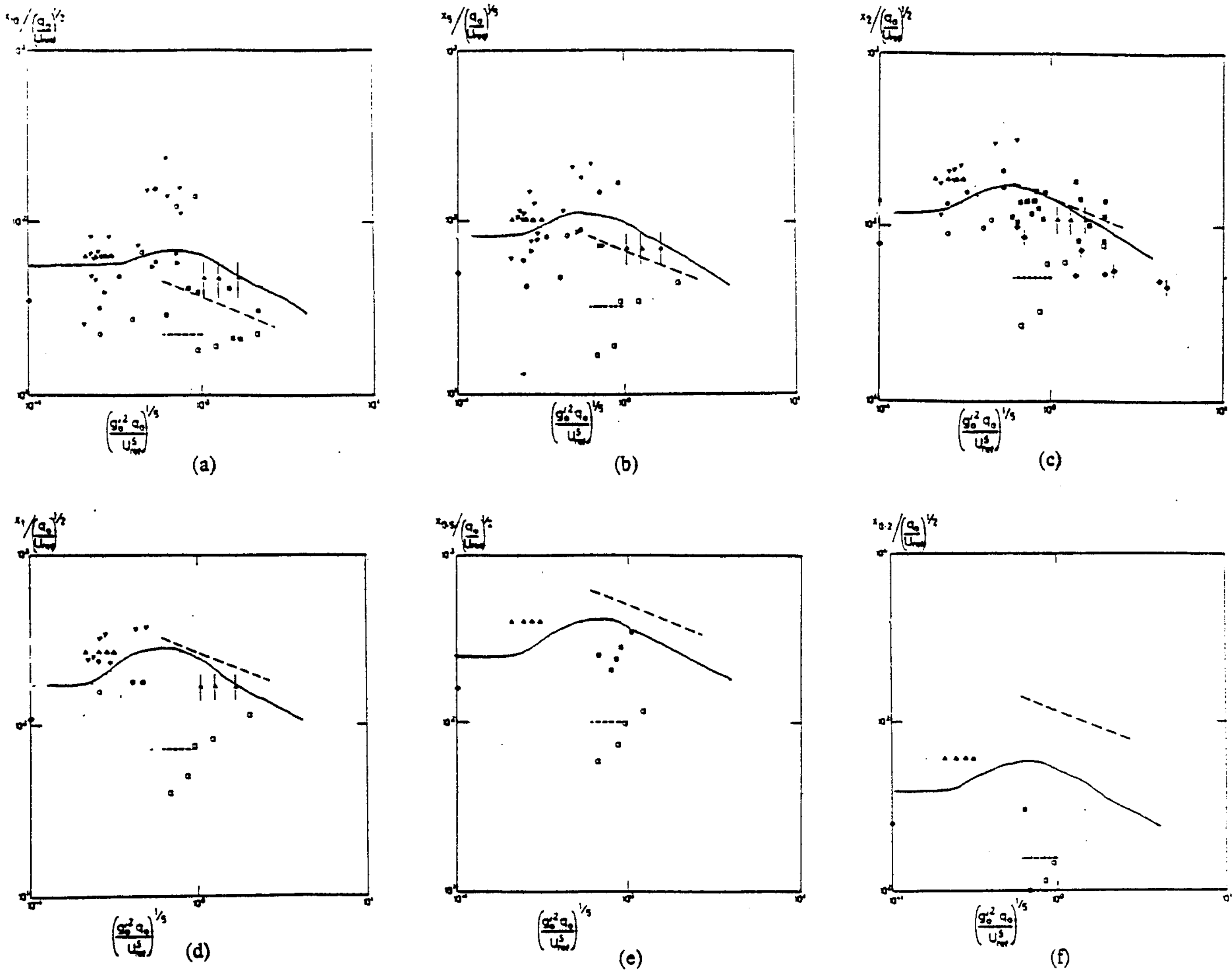


Figure 11. Graphs published by Britter and McQuaid (1988) containing experimental results for the downwind distance to a given concentration for continuous releases-laboratory data. C_m/C_o = (a)0.1(b)0.05(c)0.02(d)0.01(e)0.005(f)0.002

Conclusions from All Analyses: As a result of the extensive analysis of model uncertainty reported above, we can make the following conclusions:

Model predictions of maximum concentration (independent of position) show typical mean biases of $\pm$ 10 to 40% for the best-performing models. Typical root-mean-square errors are about 60% of the mean value, with a range from 30% to 100% for the best models.

C. COMPARISONS OF MAGNITUDE OF CONCENTRATION INCREASES DUE TO THE PRESENCE OF OBSTACLES WITH TYPICAL MODEL UNCERTAINTIES.

Section III-A presented several scenarios in which concentrations would be increased as a result of the influence of obstacles. Factor of five increases have been observed in street canyon scenarios and much larger increases are expected as the degree of confinement or sheltering increases (e.g., an enclosed courtyard in the midst of an industrial complex).

Section III-B presented the results of many model evaluation exercises, demonstrating that the relative mean bias is about $\pm$ 30% and the relative rmse is about 70% for the best model in any application. These results verify the oft-quoted "factor of two" accuracy rule for air quality models.

It is concluded that the effects of obstructions on concentrations in some scenarios (e.g., the downwind fence in Figure 6) are minor when compared with the factor-of-two model uncertainty. However, in the case of many confinement scenarios, the effects of the obstructions on concentrations are much larger than the model uncertainty (e.g., the courtyard in Figure 5).

SECTION IV

DETERMINATION OF NECESSARY MODEL COMPONENTS

There are different model types that can be used to formulate the model

Integral models (including Gaussian plume theory for passive releases) have been found to be appropriate and acceptable for passive and dense releases in unobstructed flow over flat terrain. They have also been used for passive releases near structures though their use often reduces to the incorporation of some empirical information into an integral model.

Large-eddy or direct simulation models are extremely expensive and must still be considered as research tools.

Higher-order turbulence closure models have been used to model flow around buildings and dispersion with some success though these also will not be available at a micro computer use level. If a user is dealing with a specific site and is willing to consider only a limited number of wind speeds, directions, and stabilities, then representative wind and turbulence fields may be obtained and used in a library format. Subsequent running of a dispersion code of integral or more complex type could then be undertaken on this pre-calculated flow in its entirety or in a heavily-filtered version. The latter could consist of little more than indicating different wake regions; this is probably within the capability of a microcomputer. Another possibility is to run a Lagrangian random-walk model in the computed velocity field. However, there is no evidence that satisfactory models exist of this type for an active (dense or buoyant) release.

For these reasons, integral models incorporating local empiricism offer the best approach. This approach is undoubtedly possible for simple scenarios and, with realistic expectations, can be used for more typical, complicated building arrangements.

A. PASSIVE RELEASES

Just as the literature survey has been organized by a matrix of source and receptor locations relative to the structure, the model components can be assembled using the same matrix approach. The development of an operational model will depend upon the objective decision-making process regarding selection of the appropriate submodels for each source location and plume position. For passive releases, a number of submodels for each source location already exist and have been evaluated by researchers. The emphasis in constructing a model, therefore, will be on selecting the best existing submodel and treating overlapping of the submodels and mass continuity while tracking the dispersion of a release downwind. To our knowledge, this assembly of existing submodels to construct a single model has not been done.

A flow chart for this objective decision-making process is proposed below:

Type of source--jet or area source, passive or dense gas

↓

Definition of geometry of structures and position of receptors

↓

Position of source relative to building and wind direction

↓

Calculation of building-induced transport and dispersion		
a) On building roof or face	b) In downwind recirculation cavity (near wake)	c) Far wake

↓

Estimation of parameters required for transition to "no building" dispersion model

The model components that calculate the transport and dispersion at the different receptor locations for different source locations are illustrated in Figure 12. Literature references are suggested for each submodel, for example, the plume impingement algorithm of Wilson and Netterville (1978) could be used for sources upwind of the building to estimate concentrations on the building roof or face. The plume location and size will be tracked at all distances from the source since only a portion of the plume may be intercepted by the building or turbulent building wake. Thus, for a upwind elevated source, part of the plume may impinge on the building face and be carried into the near-wake and then the far-wake, and the remainder of the plume may only be intercepted only by the far-wake. As shown in Figure 12, the plume could only be influenced by the far wake if the source location is downwind of the building outside of the near-wake.

The final box in the flow chart is also important, since it must allow for a smooth transition from the "building effects" algorithm to the "no building" dispersion model. As discussed by Hanna and Strimaitis (1988), the total mass flux must be conserved, and it is desirable to conserve the maximum concentration in the cloud or plume. Several methods for accomplishing these goals are reviewed in the reference. The lateral dimension of the cloud has the next highest priority, followed by the vertical dimension. If possible, it is desirable to use interpolation formulas for cloud entrainment so that the transition is gradual and continuous.

1. Plume Impingement Models

The simplest model (as described in Netterville and Wilson (1978)) has the building surface concentration everywhere less than the maximum concentration in the plume in the absence of the building. This impingement is assumed to take place if the vertical separation between plume and source is less than σ_z and the horizontal separation is less than σ_y. No impingement occurs outside this range. Plume impingement would apply to all surfaces without flow separation such as the upwind face.

Surfaces under regions of flow separation such as the lee face and possibly the sides may have a substantially different concentration. This

<table>
<tr><th></th><th colspan="4">SOURCE LOCATION</th></tr>
<tr><th></th><th></th><th></th><th colspan="2">Downwind of Building</th></tr>
<tr><th></th><th>Upwind of Building</th><th>On Building</th><th>Inside Cavity</th><th>Outside Cavity</th></tr>
<tr><td>On Building Roof or Face</td><td>Plume Impingement Model

Wilson and Netterville (1978)</td><td colspan="2" rowspan="2">Concentration - Distance Data Correlations

Wilson and Britter (1982)</td><td>No Effect

Concentration is zero</td></tr>
<tr><td>Within Downwind Recirculation Cavity</td><td>Plume mass intercepted by cavity
Uniformly mixed</td><td>No Effect

Concentration is zero</td></tr>
<tr><td>Within Far Wake</td><td colspan="2">Fraction into Cavity uses Cavity Release Model - Fackrell (1984)

Fraction into Far Wake uses Wake Dispersion Model - Huber and Snyder (1976) or Schulman and Hanna (1986)</td><td>Cavity Release Model

Fackrell (1984)</td><td>Fraction into far wake uses wake dispersion model</td></tr>
</table>

Figure 12. Model components that calculate the transport and dispersion at the different receptor locations for different source locations.

approach may be unduly conservative for buildings with frontal aspect ratios much different from unity.

It could be assumed that all the pollutant that impinges on the building will be carried into the recirculating region in the immediate lee of the building.

It is possible for plume material to be brought down to the ground upwind of the building within an upstream vortex - this may extend several building widths or heights (whichever is the smaller) upstream and to the sides.

2. Concentration-Distance Correlations

If the source and receptor are both on the building, the wind tunnel data of Wilson and Britter (1982) showed that

$$C_m = 9Q/(u_H r^2) \tag{1}$$

where C_m is the maximum concentration, Q the source emission rate, u_H the approach wind speed at building height, and r the shortest distance from the source to the receptor measured along the surface. However, if the source and the receptor are on the same or adjacent faces on the lower third of the building,

$$C_m = 30\ Q/(u_H r^2). \tag{2}$$

If the source is within the recirculating region (whether on the roof of the building or the near wake) Wilson and Britter (1982) also found that

$$C_m = 9\ Q/(u_H r^2) \text{ for } r/A^{1/2} < 1.73 \tag{3}$$

where A is the projected building frontal area.

These correlations can be modified to account for elevated releases above the roof where a portion of the plume is intercepted by the roof recirculation cavity or roof turbulent wake.

3. Dispersion Within the Near-Wake

It is usually argued that away from the immediate region of the source, the concentration is uniform within the recirculatory region. An early estimate of this concentration was

$$0.5 \le C_W A u_H / Q \le 2.0 \tag{4}$$

where C_W is the uniform wake concentration and A is the projected frontal area. Gifford (1976) prefers the upper bound. Wilson and Britter (1982) suggest a range of 3.0 ± 2.0, but require that $r/A^{1/2} \ge 1.73$. This ensures that the plume has traveled a sufficient distance to mix uniformly and allows for continuity with the equation for C_m.

Observations by Huber (1989) can be used to conclude that for wide buildings, the assumption of uniform mixing using the projected frontal area A is not appropriate, except perhaps for sources upwind of the building where the plume mixes around the sides and/or over the roof. A more appropriate length scale was first proposed by Wilson (1979) as

$$R = (\min(H,W)^{2/3}(\max(H,W))^{1/3} \tag{5}$$

where H is the building height and W the building width. R^2 may be more appropriate than A as the projected area for uniform mixing for sources on the building or in the near wake.

4. Cavity Release Models

If the uniform near-wake concentration is C_W, then from dimensional arguments (Fackrell, 1984 and Vincent, 1977)

$$Q = C_W \propto u_H S \tag{6}$$

where Q is the source strength in the near-wake, S is the surface area that encloses the near-wake recirculation region and $\propto$ is a constant. A time constant for the exponential decay in the near-wake can be defined as

$$t_r = V/(\alpha\ Su_H) \tag{7}$$

where V is the volume of the near-wake region. Therefore, a source term for the uniformly mixed cavity concentration can be written as

$$Q = C_w V/t_r \tag{8}$$

Fackrell (1984) defines a near-wake residence time, $\tau_R = t_r u_H/H$, and proposes from experimental data that

$$\tau_R = 11(W/H)^{3/2}/[1 + 0.6(W/H)^{3/2}] \tag{9}$$

5. Wake Dispersion Models: The Far Wake

Beyond the near-wake, the recirculating lee cavity which usually extends from 2-3 building heights downwind, Gaussian models can be applied to estimate plume dispersion. This region is characterized by descending streamlines and enhanced turbulence that may lead to substantial increases in the ground-level concentrations compared to those in the absence of the obstacle. Fackrell (1984) compared five simple Gaussian models including Gifford (1960), Turner (1969), Barker (1982), Ferrara and Cagnetti (1980) and Huber and Snyder (1976). Other model shave been proposed by Briggs (1983), Scire and Schulman (1980), Schulman and Hanna (1986), and Hunt, Britter, and Puttock (1979). Most of these models enhance the Gaussian dispersion coefficients to account for the additional turbulence introduced by the building or use a virtual source approach which assumes the source originates at a position upstream of the real source. These models are not appropriate for plume dispersion on the building or in the near-wake where plume behavior is skewed and non-Gaussian.

B. DENSE GASES

The development of a model for dense gas releases would follow the same approach as the passive release; model components for different source locations can be assembled and applied using an objective decision-making process.

1. Near Source Behavior

For downstream sources released into the recirculating cavity or the wake there is no current model for determining concentrations resulting from jets impinging on structures. The trajectory and dilution of a momentum jet may be calculated using conventional integral models if the velocity field has been estimated, including any downwash effect outside the cavity.

A momentumless source in the cavity will tend to fill the cavity laterally, unless the building is much wider than it is high. An estimate of the cavity uptake is required. This material taken up may be assumed to fill the cavity to its height. If the uptake flux is greater than the source flow, the source is easily defined. If the uptake flux is less than the source flux, the difference will spread outside the cavity region. "No-structure" calculations near the source using the flux difference will provide an estimate of the increased source width in excess of the structure width. If it is desired to maintain a uniform "integral" plume, then the information available allows an effective width to be determined and a height (weighted by structure height and plume height with no structure). Using an advection velocity in terms of a general profile will produce an effective concentration.

Note that for cases with a very wide structure compared with its height and only a small release the release will not extend fully across the wake. The source width will only extend some multiple of the structure height across the wake.

2. Downwind Cloud Development

The model should have sufficient modular structure to enable the flexibility to encompass later experimental results. A single plume formulation consistent with an integral plume model will be maintained. This will lead to some difficulty in cases of plume bifurcation particularly close to the structure.

A decision is required as to when the structures should be considered as a general roughness or treated as individual structures. In many cases this may be obvious but some objective guidance is required.

An initial view might be that the influences of all the structures of height less than the cloud height be treated as general roughness through z_o and hence u_*, whereas all taller structures should be treated individually. z_o is the roughness length and u_* is the surface friction velocity. This decision is purely pragmatic, has several useful features and the correct limits. A more correct demarcation would require "very much less than" and "very much greater than" caveats but since there is no intention of formally addressing the parameter range between these limits, that range is reduced to zero.

Note that u_* and z_o are interdependent. The role of u_* (or z_o) in model development might be made more explicit. Dense gas models frequently use u_* as some characteristic velocity describing the flow and the turbulence. This velocity is frequently used in density-influenced entrainment correlations. The data base currently available for assessing dense gas dispersion codes is not adequate for assessing whether the influence of surface roughness is adequately (though implicitly) incorporated through the change in u_*. It must be stressed that u_* (measured and estimated in the absence of the dense gas plume) is being used solely as a correlating variable with no rigorous appeal to the dynamics of the flow. It is undoubtedly the case that u_* under a dense-gas cloud will be substantially less than that in the absence of the cloud but this internal complication is bypassed when u_* is used as a correlating variable.

For various structure interactions we need to consider algorithms for trajectory, dilution and hold-up.

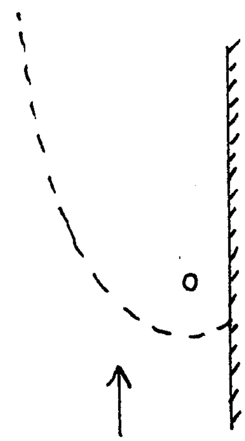
a. Trajectory

Trajectory encompasses an advection speed, its direction and any plume widening. In general, it can be argued that the plume direction is unchanged by any structure. The caveat is that a cloud interaction with a near-source structure may lead to some local direction change. But in general the cloud will go downwind. The advection speed for steady releases should be some spatially averaged advection speed, not that determined by a local structure.

For non-steady releases a similar advection speed should be used because the structure produces both regions of increased and decreased speeds. The influence of the low speed recirculating regions should make itself evident through the hold-up of material in the wake rather than through an altered advection speed.

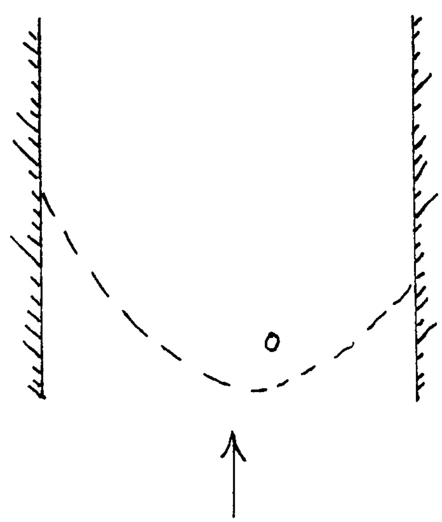
Consider the following possible algorithms for various scenario modules; restricted initially to steady flows and thus removing the complication of "hold-up."

(1) Flow parallel to single wall/fence.



Use a conventional model with width restriction. There is no doubling of concentration due to reflection; the flow will actually suffer a doubling in depth but this is spread across complete width.

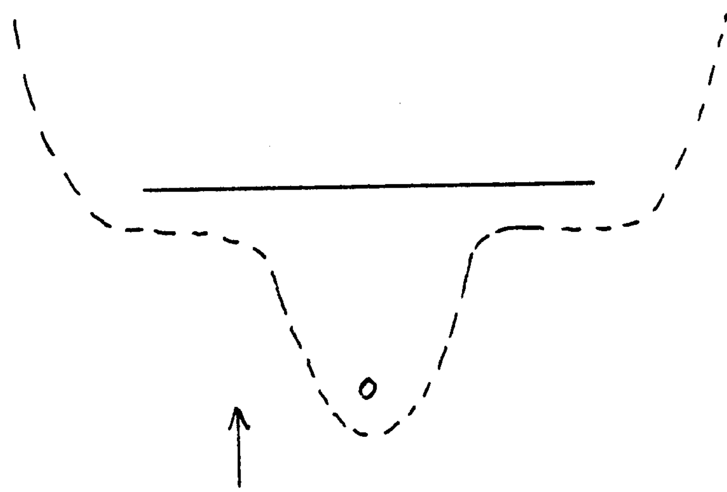
(2) Flow parallel to two walls/canyon.



As above but width restricted twice.

If the fences are of finite height then some material loss must be considered.

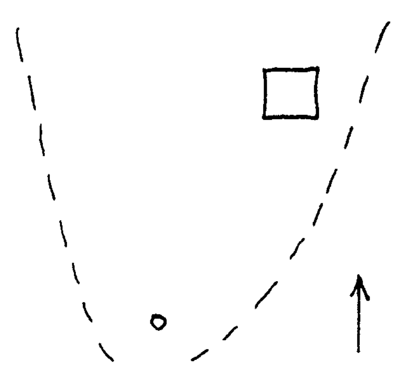
(3) Flow normal to single wall/fence/building.



Conventional model with empirical plume widening correlation. Dilution in the lee, following Britter, (1989) accommodated by a plume height increase to the fence height (or some fraction of it). Britter (1989) suggested that the plume would widen to enable it to clear the structure. If the plume can clear the structure, then the lee dilution is as if the plume was passive.

Extension to angled fences/porous fences, etc. is possible within a simple model structure but will rely on empirical results.

(4) Flow past an isolated building.



This may be modeled using a conventional plume model, with no change in trajectory, a plume widening based on some weighted sum of the plume and the building width, possibly also influenced by how wide the plume would extend if the building was two-dimensional. An objective decision must be made as to whether an interaction has taken place; what degree of overlap there is between the plume and the structure.

b. Dilution

Dilution in the lee may be estimated by assuming (Britter, 1982, 1989) that some fraction of the turbulent kinetic energy generated in the building lee is used for increasing the plume's potential energy.

This leads to the result that the plume in the immediate lee of the building should increase in depth by

$$\Delta h = \alpha \, C_D \frac{U^2}{g'} \cdot \frac{A}{hW} \tag{10}$$

$$\Delta h = \alpha \, C_D \frac{U^2}{g'} \cdot \frac{H}{h} \tag{11}$$

where α is a constant with value of about 0.1, C_D the drag coefficient, U the cloud speed, A the projected building area, h the plume depth, H the building height, W the building width, and g′ the local gravitational acceleration relating the cloud density to ambient density. Δh is restricted to be less than H - h.

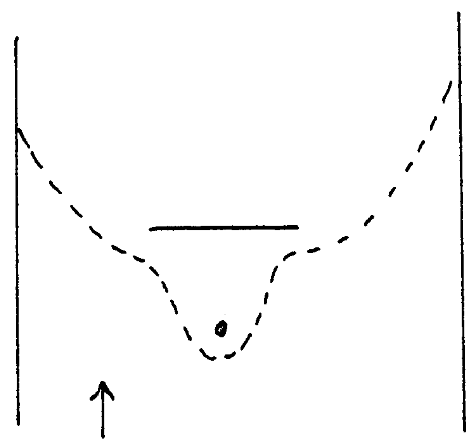
In order to return to our box model format we spread this height increase across the plume.

$$\Delta h_{box} = \Delta h \left(\frac{W}{y} \right) \tag{12}$$

where y is the width of the plume in the immediate lee of the building.

These examples could be extended to time-varying releases and instantaneous releases provided attention was paid to the time taken for released material to enter and leave recirculating regions. The use of a residence time concept will allow this treatment. However in the case of dense releases, the possibility of the material "pooling" on the ground must be considered. This will require some further empirical information on uptake rates. This alone seems to be the dominant outstanding phenomena that require substantially better understanding and parameterization.

For example:



To treat this confining structure reference to case (3) will indicate whether the side walls are relevant or not. If not, case (3) provides the solution. If the side walls restrict lateral movement, the problem becomes a two-dimensional one. The data from Britter (1989) or others results, if available, will indicate whether the release will form a pool or not. If not, case (3) is used but with no plume widening at the fence.

If however there is pooling, then some assessment of the leakage rate must be made. The appropriate parameterization for this is lacking though the work of Briggs et al. (1990) suggests an approach consistent with their data. The vapor blanket models from HEGADAS and DEGADIS and the UPTAKE model from GASTAR all address similar problems of "detrainment."

3. Model for Arbitrary Site

Development of a model that will allow treatment of an arbitrary site should draw upon the various modules that have been developed and ensure that decisions concerning module use are objectively obtained.

One approach would be to treat any interaction with the first or the first few obstacles in an individual modular way and then use some more general approach. Some "flagging" would be appropriate if situations which were difficult to incorporate within a general framework (and which led to consequences of concern) such as a diluting plume encountering a street canyon at an angle to the flow.

The general framework might be developed along the following lines:

a. Trajectory

No change though cloud widens so that any intersected structure is encompassed; some criterion for intersection is required (e.g., at least 1/2 of structure width is intersected). For a street canyon at an angle to the flow the cloud will proceed downwind, but confined by the canyon below rooftop. For a two-dimensional structure a width increase based on correlations presented earlier can be developed. This requires some modification for porous structures.

b. Dilution

Many of the observations presented earlier may be interpreted in terms of the conversion of some percentage of the turbulent kinetic energy produced by structures into potential energy (i.e., an increased cloud depth and cloud dilution). The generation rate of turbulent kinetic energy can be related back directly to the drag force on the building. There is an upper limit that a cloud that is initially less deep than a building can not be mixed to depths much greater than the buildings.

Turbulence creating structures within, say, 1H of each other would not be included in such a development.

In effect the modeling would be to allow the plume depth to increase upon encountering an obstacle such that

$$\Delta h = \alpha \left(\frac{C_D U^2 A}{g' W h} \right) \tag{13}$$

with the restriction that $h + \Delta h \leq H$.

c. Hold-up

Hold-up is partially treated through an altered velocity profile with reduced near-ground velocities, e.g., a reduced advection velocity. In addition, material enters and leaves a recirculating region at a finite rate. Typically introduction into the region may be considered rapid--possibly through a buoyancy driven velocity. Removal can be parameterized with a residence time calculation but this frequently appears as an increased longitudinal diffusion (or possibly dispersion). Of course the hold-up is not relevant to steady releases.

SECTION V

PRELIMINARY MODEL

As a demonstration of the feasibility of the modeling approach, one of the submodels or components of the passive release model have been coded and run with hypothetical data. The component selected for the preliminary model was the concentration-distance correlations based on the work of Wilson and Britter (1982). This component is used for sources and receptors located on the building or inside the near-wake recirculation region. Many of the equations for this component were initially presented in Sections IV.A.2. and IV.A.3.. Only short-stack or vent releases are treated in the preliminary model. It should be noted that this model component is preliminary and would likely be modified in a Phase II program.

As a description of the model component, if the source is within the roof recirculation cavity, the roof high turbulence zone, or the lee recirculation cavity then,

$$C_m = 9Q/(u_H r^2) \tag{14}$$

An exception is if the source and receptor are both on the lower third of the same or adjacent walls in which case,

$$C_m = 30Q/(u_H r^2) \tag{15}$$

In addition, for receptors in the recirculation cavity, this equation applies only if $r \leq 1.73R$ where $R = (\min(H,w))^{2/3}(\max(H,w))^{1/3}$. If r is greater than the larger of 1.73R or the distance to the downwind edge of the building roof, then the source is assumed to be uniformly mixed according to

$$C_w = 9Q/(u_H x_u{}^2) \tag{16}$$

where x_u is the maximum of 1.73R and the distance to the downwind roof edge.

This component requires that the positions of the roof recirculation cavity, the roof high turbulence zone, and the lee recirculation cavity be estimated mathematically so that the interaction of the source and the portion of the source intercepted by the different turbulent wakes can be calculated at each receptor location.

The length of the roof recirculation cavity (Wilson and Britter, 1982) is estimated as

$$L_c = 0.9R \tag{17}$$

The roof cavity will reattach to the building if $L_c < L$, where L is the downwind length of the building. The maximum height of the roof cavity is,

$$H_c = 0.22R \quad \text{at} \quad x = 0.5R \tag{18}$$

The high turbulence zone extends from the point of maximum roof cavity height downward at a 0.1 slope towards the end of the building.

If the roof cavity reattaches to the building, the height and width of the lee recirculation cavity or near-wake is

$$H_R = H \tag{19}$$

$$W_R = W \tag{20}$$

If the roof cavity does not reattach,

$$H_R = H + H_c \tag{21}$$

and

$$W_R = 0.6H + 1.1W \qquad \text{(Fackrell, 1982)} \tag{22}$$

In either case, the length of the lee recirculation cavity, measured from the lee face is calculated using turbulent approach flow wind tunnel measurements by Fackrell (1984),

$$L_R = 1.8W/[(L/H)^{0.3}(1.0 + 0.24(W/H))] \tag{23}$$

if $L/H < 0.3$ then $L/H = 0.3$

if $L/H > 3.0$ then $L/H = 3.0$

It should be noted that the shape of the building wakes and the gross structure of the turbulence are independent of wind speed. This is true of turbulent flow at sufficiently high Reynolds numbers.

That fraction of the plume not intercepted by the turbulent wakes remains elevated and disperses according to

$$C_m = \frac{9Q}{u_H r^2} \exp[-(H_s^2 + 2H_s \Delta H)/(2\sigma_z^2)] \tag{24}$$

where H_s is the stack height, ΔH the plume rise, and σ_z the vertical dispersion coefficient defined in Wilson and Britter (1982),

$$\sigma_z = 0.21 R^{0.25} x^{0.75} \tag{25}$$

The model was run for two hypothetical buildings. In this initial demonstration version, all of the plume material was assumed to be within the turbulent wake, although the fraction below the high turbulence region was still calculated and printed. The first building was 10 m high, 40 m wide, and 40 m long ($H = 10$, $W = 40$, $L = 40$). The second building was a 20 m cube ($H = W = L = 20$ m). A flush roof vent was placed at the upwind edge of each building. For each vent, 1 m/s and 5 m/s wind speeds were run. The vent diameter was set at 0.3 m.

For the first building, the calculated roof recirculation cavity reached a maximum height of 3.5 m at a distance of about 8 m from the upwind edge. The cavity reattached to the roof at about 14 m downwind. The near-wake recirculation cavity was calculated to have a length of 26 m, a height of 10 m, and a width of 50 m.

For the second building, the maximum height of the roof recirculation cavity was 4.4 m at a distance of 10 m from the upwind edge. The cavity also reattached to the roof for this case, but not until 18 m downwind, or nearly

at the end of the building. The near-wake recirculation cavity was estimated as 29 m long, 20 m high, and 34 m wide.

The calculated downwind concentration profiles for the two building cases are shown in Table 1a and 1b. Because the sources were placed on the upward edge of both buildings and were flush roof vents, the maximum concentrations always occurred near the source. For the first building, Table 1a shows that the highest calculated concentrations occurred with 1 m/s winds because of the lower dilution. The concentration profiles are, in fact, different by the ratio of wind speeds or a factor of 5. This is because all the plume material was modeled using equation (14) which is inversely proportional to u_H. The calculated fraction of plume mass below the high turbulence region is higher for the higher wind speed because the momentum plume rise is lower.

The distance from the source to the downwind edge of the building is greater than 1.73R, so that the plume is considered uniformly mixed throughout the entire near-wake.

The results of the second building are shown in Table 1b. Once again, the concentrations are different by a factor of 5 for the 1 m/s and 5 m/s wind speeds because of the inversely proportional influence of diluting wind speed.

Unlike the first building, the distance to uniform mixing did not occur to about 35 m downwind, or 15 m beyond the downwind edge of the building in the near-wake.

On the roof, the concentration profiles are the same for both buildings because the source characteristics are identical. The near-wake, however, is further downwind for the first building, however, so the uniform near-wake concentrations are lower.

Table 1

Predicted Concentrations at Receptors Along Building Roof, Downwind Wall, and in Downwind Cavity Wake Region

(a) Emission rate: 1 g/s. Building Dimensions: Width=40 m, Length=40 m, Height=10 m.

			Wind Speed = 1.0 m/s					Wind Speed = 5.0 m/s				
RECEPTOR NO.	XDIST (m)	SDIST (m)	Delta Z (m)	Z2 (m)	Z3 (m)	FRACBZ2	CHI (g/m**3)	Delta Z (m)	Z2 (m)	Z3 (m)	FRACBZ2	CHI (g/m**3)
1	5.0	5.0	2.51	3.02	3.02	0.64	3.60E-01	0.44	3.02	3.02	0.97	7.20E-02
2	10.0	10.0	3.17	3.29	3.81	0.52	9.00E-02	0.56	3.29	3.81	0.88	1.80E-02
3	15.0	15.0	3.60	2.79	4.36	0.40	4.00E-02	0.64	2.79	4.36	0.75	8.00E-03
4	20.0	20.0	3.60	2.29	4.80	0.37	2.25E-02	0.71	2.29	4.80	0.66	4.50E-03
5	25.0	25.0	3.60	1.79	5.17	0.35	1.44E-02	0.72	1.79	5.17	0.59	2.88E-03
6	30.0	30.0	3.60	1.29	5.50	0.33	1.00E-02	0.72	1.29	5.50	0.54	2.00E-03
7	35.0	35.0	3.60	0.79	5.79	0.32	7.35E-03	0.72	0.79	5.79	0.50	1.47E-03
8	40.0	40.0	3.60	0.29	6.05	0.31	5.63E-03	0.72	0.29	6.05	0.47	1.13E-03
9	40.0	45.0	3.60	0.29	6.05	0.29	5.63E-03	0.72	0.29	6.05	0.46	1.13E-03
10	40.0	50.0	3.60	0.29	6.05	0.29	5.63E-03	0.72	0.29	6.05	0.46	1.13E-03
11	50.0	60.0	3.60	-	6.52	0.32	5.63E-03	0.72	-	6.52	0.46	1.13E-03

(b) Emission rate: 1 g/s. Building Dimensions: Width=20 m, Length=20 m, Height=20 m.

			Wind Speed = 1.0 m/s					Wind Speed = 5.0 m/s				
RECEPTOR NO.	XDIST (m)	SDIST (m)	Delta Z (m)	Z2 (m)	Z3 (m)	FRACBZ2	CHI (g/m**3)	Delta Z (m)	Z2 (m)	Z3 (m)	FRACBZ2	CHI (g/m**3)
1	5.0	5.0	2.51	3.53	3.53	0.75	3.60E-01	0.44	3.53	3.53	0.98	7.200E-02
2	10.0	10.0	3.17	4.40	4.44	0.69	9.00E-02	0.56	4.40	4.44	0.94	1.800E-02
3	15.0	15.0	3.60	3.90	5.09	0.53	4.00E-02	0.64	3.90	5.09	0.83	8.000E-03
4	20.0	20.0	3.60	3.40	5.60	0.48	2.25E-02	0.71	3.40	5.60	0.74	4.500E-03
5	20.0	25.0	3.60	3.40	5.60	0.20	1.44E-02	0.71	3.40	5.60	0.43	2.880E-03
6	20.0	30.0	3.60	3.40	5.60	0.20	1.00E-02	0.71	3.40	5.60	0.43	2.000E-03
7	20.0	35.0	3.60	3.40	5.60	0.20	7.52E-03	0.71	3.40	5.60	0.43	1.504E-03
8	20.0	40.0	3.60	3.40	5.60	0.20	7.52E-03	0.71	3.40	5.60	0.43	1.504E-03
9	25.0	45.0	3.60	2.90	6.03	0.23	7.52E-03	0.72	2.90	6.03	0.44	1.504E-03

Definitions:
- XDIST - Distance from upwind bldg. edge to receptor
- SDIST - Distance along surface of bldg. from upwind bldg. edge to receptor
- Delta Z - Plume rise due to momentum
- Z2 - Height above the roof of the high turbulence region
- Z3 - Height above the roof of the roof wave boundary
- FRACBZ2 - Fraction of plume's mass below Z2
- CHI - Predicted concentration

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The literature review leads to the following conclusions:

(1) In the case of passive gas releases on or near simple structures, adequate laboratory and field data and empirical/similarity models exist for several different source locations. However, a simple comprehensive model has not been assembled from these components.

(2) In the case of dense gas releases on or near simple structures, much data exist but relatively little analysis has been done and few general models have been proposed.

(3) Less information is available for releases from positions more than one obstacle height upwind or downwind of the obstacle.

(4) Only a few specialized experiments have been carried out for complex confinement situations, such as street canyon networks or courtyards.

(5) The magnitudes of increases in concentrations due to the influence of obstacles are larger than the levels of uncertainty of model predictions for many types of source scenarios. Concentration increases of factors of 5 to 10 or more can occur in confinement scenarios.

The information (data and formulas) in the literature was used to develop a preliminary model that should form a basis for a concerted model development and evaluation effort in the future. A preliminary model code was written and tested that contains many of the desired components. This code can be the basis for further development in Phase II of the project.

As a result of this Phase I research program, the following recommendations are made:

A) Existing dense gas data sets should be acquired and analyzed, with the goal of development of specific technical algorithms (e.g., formulas for the dilution of a dense gas cloud on either side of a fence).

B) Plans should be made for the laboratory and field experiments necessary to fill in missing pieces in the comprehensive model, with emphasis on confinement scenarios.

C) A comprehensive model should be put together for use on PC's. The model should apply to many types of obstacle configurations, source types and densities, and source-obstacle geometries.

D) The new model should be evaluated with a wide variety of field and laboratory data and sensitivity tests should be carried out for the full range of possible input conditions.

REFERENCES - DENSE GAS RELEASES

Bradley, C.I., & R.J.Carpenter 1983: The simulation of dense vapour cloud dispersion using wind tunnels and water flumes. Proc. 4th Intl Symp. Loss Prevention and Safety Promotion inthe Process Industries, Harrogate, IChemE, UK, 1216 Sept. 1983, Vol.1, 56-65.

Briggs, G.A., R.S. Thompson & W.H. Snyder, 1990: Dense gas removal from a valley by crosswinds. *J. Hazardous Materials*.

Brighton, P.W.M., 1986: Heavy-gas dispersion from sources inside buildings or in their wakes. I Chem E Symposium on "Refinement of Estimates of the Consequences of Heavy Toxic Vapour Releases". UMIST.

Brighton, P.W.M., 1988: Similarity solutions for two dimensional steady gravity currents. UK Atomic Energy Authority Report SRD R444.

Brighton, P.W.M., 1988: Similarity solutions for two dimensional steady gravity currents. Proc. IMA Conference on Stably Stratified Flow and Dense Gas Dispersion, Chester, UK, 910 April 1986 (ed. J.S. Puttock). Oxford University Press.

Brighton, P.W.M., 1989: The effects of natural and manmade obstacles on heavy gas dispersion. Safety and Reliability Directorate, United Kingdom Atomic Energy Authority. Draft Report

Brighton, P.W.M., & A.J. Prince 1987: Overall properties of the heavy gas clouds in the Thorney Island Phase II Trials. *J. Hazardous Materials*, 16, 103-138.

Britter, R.E., 1982: Special topics on dispersion of dense gases. Report on Contract No. 1200/01.01, Research and Laboratory Services Division, UK Health and Safety Executive, Sheffield.

Britter, R.E., 1989: Experiments on some effects of obstacles on dense-gas dispersion. SRD R 407, Safety and Reliability Directorate, United Kingdom Atomic Energy Authority, Wigshaw Lane, Culceth, Warrington, WA3 4NE, United Kingdom.

Britter, R.E., 1990: Gastar User Manual, version 2.2, Cambridge Environmental Research Consultants, Sheraton House, Castle Park, Cambridge, England CB3 OAX.

Britter, R.E. and J. McQuaid, 1988: Workbook on the dispersion of dense gases. HSE Cont. Res. Rep. No. 17/1988, HSE, Sheffield, S3 7HQ, United Kingdom.

Britter, R.E., & W.H. Snyder, 1988: Fluid modeling of dense gas dispersion over a ramp. *J. Hazardous Materials*, 18, 37-67.

Davies, M.E., & S. Singh, 1985: The phase II trials: a data set on the effect of obstructions. *J. Hazardous Materials*, 11, 301-323.

Deaves, D.M., 1985: 3-Dimensional model predictions for the upwind building trial of Thorney Island Phase II. *J. Haz. Mat.*, 11, 341-346.

Dirkmaat, J.J., 1981: Experimental studies on the dispersion of heavy gases in the vicinity of structures and buildings. Symposium on Designing with the Wind, Nantes, France, 1519 June 1981, Paper III-3.

Duijm, N.J., 1987: Effects of reynolds number on windtunnel simulation of the dispersion of heavy gas clouds around a building. T.N.O. report no. 87351/R.24/NVE.

Fannelop, T.K., & F. Zumsteg 1986: Special problems in heavy gas dispersion. *Heavy Gas and Risk Assessment III* (ed. S. Hartwig), D. Reidel 123-135.

Guldemond, C.P., 1986: The behavior of denser than air ammonia in the presence of obstacles wind tunnel experiments. *Plant/Operations Progress*, 5(2), 93-96.

Hanna, S.R., D.G. Strimaitis, J.C. Chang, 1990: Evaluation of 14 hazardous gas models with ammonia and hydrogen fluoride field data. To appear in *J. Hazardous Materials*.

Jensen, N.O., 1984: On the dilution of a dense gas plume: investigation of the effect of surface mounted obstacles. Proc. IUTAM Symposium on Atmospheric Dispersion of Heavy Gases and Small Particles, Delft, the Netherlands, 29 Aug - 2 Sept 1983 (ed. G. Ooms & H. Tennekes), Springer-Verlag 115-127.

Jindal, M., M.S. thesis from North Carolina State Univ.

Knudsen, S., & P.A. Krogstad 1987: A wind tunnel simulation of the Thorney Island Phase II trial 20. *J. Hazardous Materials*, **16**, 173-183.

Konig, G., 1987: Windkanalmodellierung der Ausbreitung stofallartig freigesetzter Gase schwerer als Luft. *Hanburger Geophysikalische Einzelschriften, Series A*, No 85.

Konig, G., & M. Schatzmann, 1986: Experimentelle untersuchung des einflusses von gebaudeformationen auf die ausbreitung schwerer gase. BMFTForschungsvorhaben RGB 8324.

Kothari, K.M., & R.N. Meroney, 1982: Accelerated dilution of liquefied natural gas plumes with fences and vortex generators. Gas Research Institute Report GRI 81/0074.

Kothari, K.M., R.N. Meroney, & D.E. Neff, 1981: LNG plume interaction with surface obstacles. Gas Research Institute Report GRI 80/0095.

Krogstad, P.A., & R.M. Pettersen, 1986: Wind tunnel modeling of a release of a heavy gas near a building. *Atmos. Env.*, **20**, 867-878.

Lamb, V.R., & R.E. Britter, 1984: Shallow flow over an isolated obstacle. *J. Fluid Mech.*, **147**, 291-313.

Marotzke, K., 1988: Wind tunnel modeling of density current interaction with surface obstacles. Meeting of the CEC Project BA at TNO in Apeldoorn, The Netherlands, Sept. 29-30, 1988.

McQuaid, J., 1986: Some effects of obstructions on the dispersion of heavy gas clouds. Symposium on Refinement of Estimates of the Consequences of Heavy Toxic Vapour Release, Manchester, UK, 8 Jan 1986. I. Chem. E. North Western Branch Papers 1986 No. 1.

Mcquaid, J. (ed.) 1987: Heavy gas dispersion trials at Thorney Island - 2. *J. Hazardous Materials*, 16.

McQuaid, J., & B. Roebuck, 1985: Large scale field trials on dense vapour dispersion. Commission of the European Communities Report EUR 10029en.

Melia, & R.E. Britter, 1990: The influence of obstacle arrays on dense gas dispersion. To appear in I.M.A. Proceedings.

Petersen, R.L., 1989: Effect of homogeneous and heterogeneous surface roughness on heavier-than-air gas dispersion. 6th U.S. Nat. Conf. on Wind Engin., Houston.

Petersen, R.L., & R. Diener, 1990: Vapour barrier assessment programme for delaying and diluting heavier-than-air HF vapour clouds -- a wind tunnel modeling evaluation. *J. Loss Prev. Process Ind.*, 3, 187196.

Petersen, R.L., & M.A Ratcliff, 1989: Effect of homogeneous and heterogeneous surface roughness on heavier-than-air gas dispersion. Vols. I and II., API Pub. Nos. 4491 and 4492, American Petroleum Institute, 1220 L St. NW, Washington, DC 20005.

Riethmuller, M.L., 1986: Effect of distributed obstacles on the dispersion of a heavy gas cloud. Von Karman Institute for Fluid Dynamics Report EAR 8208.

Rottman, J.W., J.E. Simpson, J.C.R. Hunt, and R.E. Britter, 1985: Unsteady gravity current flows over obstacles: Some observations and anlysis related to the Phase II trials. *J.Haz. Materials*, 11, 325-340.

Turner, J.T., 1973: Buoyancy effects in fluids. Cambridge University Press.

White, B.R., 1987: WindTunnel wake measurements of heavierthanair gas dispersion near a two dimensional obstacle. *Boundary Layer Meteorol.*, 38, 105-124.

REFERENCES - PASSIVE GAS RELEASES

Benarie, M.M., 1987: The limits of air pollution modeling. *Atmos. Environ.*, **21**, 1-5.

Briggs, G.A., 1973: Diffusion estimation for small emissions. In *Atmospheric Turbulence and Diffusion Laboratory 1973 Annual Report.* Publication No. ATDL-106, NOAA/ATDL, Oak Ridge, TN.

Britter, R.E. and J.C.R. Hunt, 1979: Velocity measurements and order of magnitude estimates of the flow between two buildings in an atmospheric boundary layer. *J. Industrial Aerodynamics,* **4**, 165-182.

Britter, R.E., J.C.R. Hunt and J.S. Puttock, 1976: Predicting pollution concentrations near buildings and hills. Presented at the Conference on Systems and Models in Air and Water Pollution at the Institute of Measurement, London, September 22-24.

Cagnetti, P., 1975: Downwind concentrations of an airborne tracer released in the neighborhood of a building. *Atmos. Environ.,* **9**, 739-747.

Carson, D.J., 1986: A report on the symposium in uncertainty in modeling atmospheric dispersion. *Atmos. Environ.*, **20**, 1047-1049.

DiCristofaro, D.C., S.R. Hanna, M.T. Baer, 1990: The offshore and coastal dispersion (OCD) model. Proceedings, 19th ITM on Air Pollution Modeling and Its Application, Vancouver, B.C., NATO/CCMS.

Fackrell, J.E., 1984: An examination of simple models for building influenced dispersion. *Atmos. Environ.*, **18**, 89-98.

Fackrell, J.E., 1984: Parameters characterizing dispersion in the near wake of buildings. *Journal of Wind Engineering and Industrial Aerodynamics,* **16**, 97-118.

Fackrell, J.E., 1982: Flow behaviour near isolated rectangular buildings, CEGB Rep. TPRD/M/1254/N82.

Fox, D.J., 1984: Uncertainty in air quality modeling. *Bull. Am. Meteorol. Soc.,* **64**, 27-36.

Guenther, A., B. Lamb and E. Allwine, 1990: Building wake dispersion at an arctic industrial site: Field tracer observations and plume model evaluations. Submitted to *Atmos. Environ.*

Guenther, A., B. Lamb and R. Petersen, 1989: Modeling of plume downwash and enhanced diffusion near buildings: Comparison to wind tunnel observations for an arctic industrial site. *J. Appl. Meteor.,* 28, 343-353.

Guenther, A., B. Lamb and D. Stock, 1990: Numerical simulation of plume downwash at an arctic industrial site. Submitted to *J. Appl. Meteor.*

Halitsky, J., 1965: Estimation of stack height required to limit contamination of building air intakes. *Amer. Indus. Hygiene Assoc. Journal,* **26**, 106-116.

Halitsky, J., 1977: Wake and dispersion models for the EBR-II building complex. *Atmos. Environ.*, 11, 577-596.

Halitsky, J., 1989: A jet plume model for short stacks. *JAPCA*, 39, 856-858.

Halitsky, J., 1990: Calculation of a plume centerline over a building. Submitted to *JAPCA*.

Halitsky, J., 1990: Calculation of minimum available atmospheric dilution downwind of building exhausts. *ASHRAE Trans.*, **96**, Part 1.

Hanna, S.R., J.C. Chang, 1990: Revision of the hybrid plume dispersion model (HPDM) for application to urban areas. Proceedings, 18th ITM on Air Pollution Modeling and Its Application, Vancouver, BC, NATO/CCMS.

Hanna, S.R., G.D. Strimaitis, J.C. Chang, 1990: The influence of measurement uncertainties on the performance of air quality models. Proceedings, EPA/AWMA International Symposium on Measurement of Toxic and Related Air Pollutants.

Hanna, S.R. and P.J. Drivas, 1987: Guidelines for use of vapor cloud dispersion models. CCPS/AIChE, 345 E. 47th St., New York, NY 10017, 177.

Hatcher, R.V. and R.N. Meroney, 1977: Dispersion in the wake of a model industrial complex. In *Preprints of Joint Conference on Applications of Air Pollution Meteorology*. Salt Lake City, Nov. 29-Dec. 2, Amer. Meteorol. Soc., Boston, MA, pp 343-346.

Hatcher, R.V., R.N. Meroney, J.A. Peterka and K. Kothari, 1978: Dispersion in the wake of a model industrial complex. U.S. NRC Report NUREG-0373, NTIS, Springfield, VA, 231 pp.

Hosker, R.P., Jr., 1980: Dispersion in the vicinity of buildings. In *Proc. of Second Joint Conf. on Applic. of Air Poll. Meteorology and Second Conference on Indust. Meteor.*, March 24-28, New Orleans, LA, American Meteor. Soc., Boston, MA.

Hosker, R.P., Jr., 1982: Methods for estimating wake flow and effluent dispersion near simple block-like buildings. U.S. Nucl. Reg. Comm., Report NUREG/CR-2521 and NOAA Tech. Memo ERL-ARL-108. NOAA/ERL, Atmos. Turb. and Diff. Lab., Oak Ridge, TN, 138 pp.

Hosker, R.P., Jr., 1985: Flow around isolated structures and building clusters: A review. *ASHRAE Trans.*, **91**, Part 2.

Hosker, R.P., Jr. and W.R. Pendergrass, 1986: Flow and dispersion near clusters of buildings. U.S. NRC Report NUREG/CR-4113, NTIS, Springfield, VA, 96 pp.

Hosker, R.P., Jr., 1987: The effects of buildings on local dispersion. Modeling the urban boundary layer. pp 95-160, American Meteor. Soc., Boston, MA.

Hoydysh, W.G. and L.L. Schulman, 1987: Fluid modeling study of the contamination of fresh air intakes from roof top emissions. Paper 87-82A.9 at 80th Annual Meeting of APCA, New York.

Huber, A.H., 1977: Incorporating building/terrain wake effects on stack effluents. In *Preprints of Joint Conference on Applications of Air Pollution Meteorology.* Salt Lake City, Nov. 29-Dec. 2, Amer. Meteorol. Soc., Boston, MA.

Huber, A.H., 1979: An evaluation of obstacle wake effects on plume dispersion. Presented at Fourth Symposium on Turbulence, Diffusion, and Air Pollution. Reno, NV, Jan. 15-18, Amer. Meteorol. Soc., Boston, MA.

Huber, A.H., 1984: Evaluation of a method for estimating pollution concentrations downwind of influencing buildings. *Atmos. Environ.,* **18**, 2313-2338.

Huber, A.H., 1986: A look at the influence of building orientation on plume dispersion in the wake of a building. Fifth Joint Conference on Applications of Air Pollution Meteorology, 18-21 November, Chapel Hill, NC.

Huber, A.H., 1988: Performance of a Gaussian model for centerline concentrations in the wake of buildings. *Atmos. Environ.,* **22**, 1039-1050.

Huber, A.H., 1988: Video images of smoke dispersion in the near wake of a model building. Part I. Temporal and spatial scales of vortex shedding. *J. Wind Engr. Ind. Aerodyn.*

Huber, A.H., 1989: The influence of building width and orientation on plume dispersion in the wake of a building. *Atmos. Environ.,* **23**, 2109-2116.

Huber, A.H. and S.P.S. Arya, 1988: Video images of smoke dispersion in the near wake of a model building. Part II. Cross-stream distribution. *J. Wind Engr. Ind. Aerodyn.*

Huber, A.H. and W.B. Petersen, 1989: Simulating concentration fluctuations in the wake of a building using a Gaussian integrated puff model. Sixth Joint Conference on Applications of Air Pollution Meteorology, 30 January-3 February, Anaheim, CA.

Huber, A.H. and W.H. Snyder, 1976: Building wake effects on short stack effluents. In *Preprints of Third Sympos. on Atmospheric Turbulence, Diffusion, and Air Quality.* Raleigh, NC, Oct. 19-22, Amer. Meteorol. Soc., Boston, MA.

Huber, A.H. and W.H. Snyder, 1982: Wind tunnel investigation of the effects of a rectangular-shaped building on dispersion of effluents from short adjacent stacks. *Atmos. Environ.,* **16**, 2837-2848.

Hunt, J.C.R., 1981: Mechanisms for dispersion of pollutants around buildings and vehicles. *Proc. Conf. on Vehicle Exhaust Impacts in the Vicinity of Major Streets*, Oct. 20-21, TUEV Rheinland, Cologne, West Germany, pp. 235-268.

Irwin, J.S., A.H. Huber and W.B. Petersen, 1990: Estimating exposures downwind of isolated buildings. EPA/A&WMA International Symposium on Measurement of Toxic and Related Pollutants, 30 April-4 May, Raleigh, NC.

Isyumov, N. and H. Tanaka, 1979: Wind tunnel modeling of stack gas dispersion--difficulties and approximations. *Proc. Fifth Intern. Conf. and Wind Engineering*, Fort Collins, CO.

Johnson, W.B., E. Shelar, R.E. Ruff, H.B. Singh and L. Salas, 1975: Gas tracer study of roof-vent effluent diffusion at Millstone Nuclear Power Station. Atomic Industrial Forum Report AIF/NESP-007b, Stanford Research Institute, Palo Alto, CA, 295 pp.

Kim, S., H. Brandt, and R.R. White, 1989: An experimental study of two-dimensional atmospheric gas dispersion near two objects. *Boundary-Layer Meteorlogy*, 52, 1-16.

Kothari, K.M., J.A. Peterka and R.N. Meroney, 1980: The wake structure behind a model industrial complex. U.S. NRC Report NUREG/CR-1473, NTIS, Springfield, VA.

Logan, E., Jr. and D.S. Barber, 1980: Effects of lateral spacing on wake characteristics of buildings. NASA Contractor Report CR-3337, NTIS, Springfield, VA, 74 pp.

Meroney, R.N., 1982: Turbulent diffusion near buildings. Ch. 11 in *Engineering Meteorology*. E.J. Plate, ed., Elsevier Scientific Publishing Co., Amsterdam, 481-525.

Munn, R.E. and A.F.W. Cole, 1967: Turbulence and diffusion in the wake of a building. *Atmos. Environ.*, 1, 33-43.

Peterka, J.A., R.N. Meroney and K.M. Kothari, 1985: Wind flow patterns about buildings. *J. Wind Engin. and Indus. Aero.*, 21, 21-38.

Petersen, W.B. and A.H. Huber, 1990: Concentration fluctuations of a toxic material downwind of a building. EPA/A&WMA International Symposium on Measurement of Toxic and Related Air Pollutants, 30 April-May 4, Raleigh, NC.

Petersen, R.L. and D.J. Wilson, 1989: Analytical versus wind tunnel determined concentrations due to laboratory exhaust. *ASHRAE Trans 95*, Pt. 2.

Puttock, J.S., 1978: Modeling the effects of wakes behind hills and buildings on pollutant dispersion. *Proc. 9th NATO-CCMS Int. Tech. Meeting on Air Pollution Modeling and its Applications*. Toronto, Canada.

Ramsdell, J.V., Jr., 1989: Diffusion in building wakes for ground-level releases. Submitted to *Atmos. Environ.*

Robins, A.G. and I.P. Castro, 1977: A wind tunnel investigation of plume dispersion in the vicinity of a surface mounted cube - I. The flow field. *Atmos. Environ.*, **11**, 291-297.

Robins, A.G. and I.P. Castro, 1977: A wind tunnel investigation of plume dispersion in the vicinity of a surface mounted cube - II. The concentration field.. *Atmos. Environ.*, **11**, 299-311.

Robins, A.G. and J.E. Fackrell, 1980: Laboratory studies of dispersion near buildings. *Proc. CEC Symp. on Radioactive Releases and their Dispersion in the Atmosphere.* Risø, Denmark

Robins, A.G. and J.E. Fackrell, 1983: Mean concentration levels around buildings due to nearby low-level emissions. Report No. TPRD/M/1261/N82, CEGB, Leatherhead, U.K.

Schulman, L.L. and S.R. Hanna, 1986: Evaluation of downwash modifications to the Industrial Source Complex Model. *J. Air Poll. Control Assoc.*, **36**, 258-264.

Snyder, W.H. and R.E. Lawson, Jr., 1990: Fluid modeling simulation of stack-tip downwash. Submitted to *Atmos. Environ.*

Start, G.E., J.H. Cate, C.R. Dickson, N.R. Ricks, G.R. Ackermann and J.F. Sagendorf, 1977: Rancho Seco building wake effects on atmospheric diffusion. NOAA Tech. Memo, ERL-ARL-69, NOAA/ARL, Idaho Falls, ID, 185 pp.

Start, G.E., N.F. Hukari, J.F. Sagendorf, J.H. Cate and C.R. Dickson, 1980: EOCR building wake effects on atmospheric diffusion. U.S. NRC Report NUREG/CR-1395, NOAA Tech. Memo. ERL-ARL-91, NTIS, Springfield, VA.

Thuillier, R.H., 1981: Dispersion characteristics in the lee of complex structures. 74th Annual Meeting of the Air Pollution Control Assoc., Paper 81-62.3, 21-26 June, Philadelphia, PA.

Thuillier, R.H. and R.L. Mancuso, 1980: Building effects on effluent dispersion from roof vents at nuclear power plants. EPRI Report No. NP-1380, Project No. 1073-1. Electric Power Research Institute, Palo, Alto, CA, 218 pp.

Turfus, C., 1988: Calculating mean concentrations for steady sources in recirculating wakes by a particle trajectory method. *Atmos. Environ.*, **22**, 1271-1290.

Venkatram, A., 1988: Inherent uncertainty in air quality modeling. *Atmos. Environ.* **22**, 1221-1227.

Vincent, J.H., 1977: Model experiments on the nature of air pollution transport near buildings. *Atmos. Environ.*, **11**, 765-774.

Vincent, J.H., 1978: Scalar transport in the near aerodynamic wakes of surface-mounted cubes. *Atmos. Environ.*, **12**, 1319-1322.

Wilson, D.J., 1979: Flow patterns over flat-roofed buildings and application to exhaust stack design. *ASHRAE Trans.*, 85, 284-295.

Wilson, D.J., 1983: A design procedure for estimating air intake contamination from nearby exhaust vents. *ASHRAE Trans.*, 89, 136-152.

Wilson, D.J. and R.E. Britter, 1982: Estimates of building surface concentrations from nearby point sources. *Atmos. Environ.*, 16, 2631-2646.

Wilson, D.J. and E. Chui, 1985: Influence of exhaust velocity and wind incidence angle on dilution from roof vents. *ASHRAE Trans.*, 91.

Wilson, D.J. and E. Chui, 1987: Effect of turbulence from upwind buildings on dilution of exhaust gas. *ASHRAE Trans.*, 93.

Wilson, D.J. and D.D.J. Netterville, 1978: Interaction of a roof-level plume with a downwind building. *Atmos. Environ.*, 12, 1051-1059.

Wilson, D.J. and Winkel, 1982: The effect of varying exhaust stack height on contaminant concentration at roof level. *ASHRAE Trans.*, 88, 515-533.

Wise, A.F.E., 1971: Effects due to groups of buildings. *Phil. Trans. Roy. Soc. Lond. A.*, 269, 469-485.

Yamartino, R.J. and G. Wiegand, 1986: Development and evaluation of simple models for the flow, turbulence and pollutant concentration fields within an urban street canyon. *Atmos. Environ.*, 20, 2137-2156.

APPENDIX A

BRIEF OVERVIEWS OF RELEVANT PAPERS ON EFFECTS OF OBSTACLES ON PLUMES

A-I

SUMMARY OF PAPERS ON EFFECTS OF OBSTACLES ON PASSIVE GAS PLUMES

Title: Velocity measurements and order of magnitude estimates of the flow between two buildings in an atmospheric boundary layer.

Author: Britter, R.E. and J.C.R. Hunt

Publication: J. Industrial Aerodynamics, 1979, Vol. 4, pp 165-182.

Findings:

(1) Recirculating vortex between low wide building of height h and tall downwind building of height H and width W separated by distance L shows weak interaction when $L > 6\,h$ and $L > 3\,W$ and strong interaction when $L < 6\,h$ and $L < 3\,W$.

(2) The return vortex flow is amplified by the two buildings and is a maximum when $L = 2/3\,W$. The maximum speed is about the sum of the maximum speeds for each isolated building and is higher than the upwind approach speed at height h. The amplification is independent of H if $H >> h$ and $H >> W$.

(3) Mathematical model of amplification agrees well with wind tunnel observations.

(4) Turbulence measurements with pulsed hot-wire anemometer have error of about 8%.

Relevancy to AF Project:

The wind tunnel experiments and simple model of wind speed amplification between two buildings has much relevance to the AF study. The paper points out the need for careful turbulence measurements and the uncertainties involved.

Title: An examination of simple models for building influenced dispersion

Author: Fackrell, J.E.

Publication: Atmospheric Environment, 1974, Vol. 18, pp 89-98

Five Gaussian plume models that enhance dispersion to simulate building downwash were compared with wind tunnel and full-scale concentration data.

The models are:

(a) Gifford (1960): *Nuc. Saf.*, 2, 56-59, which uses $(\pi \sigma_y \sigma_z + cA)$.

(b) Turner (1969): *Workbook of Atmospheric Dispersion*, uses virtual source.

(c) Barker (1982): CEGB Report No. TPRD/B/0072/N82, uses virtual source.

(d) Ferrara and Cagnetti (1980): Commission of European Communities Seminar, Riso, Denmark.
$\sigma_y{}' = \sigma_y + W/2.5$, $\sigma_z{}' = \sigma_z + H/2.5$

(e) Huber and Snyder (1976): 3rd Symposium on atmospheric turbulence diffusion and air quality, Raleigh, N.C., which enhance σ_y, σ_z for $3\ H < x < 10\ H$ and use virtual source for $x \geq 10\ H$.

The data are:

(a) Dean and Robins (1981): Unpublished M.S. thesis, wind tunnel tests, 6 rectangular bldgs., 3 release heights, (ground, roof, downwind stack), 0° and 45°; 27 tests.

(b) Fackrell and Robins (1981): CEGB Report No. RD/M/1172/R81, wind tunnel tests, AGR nuclear station, ground level and roof sources every 45° (therefore upwind and downwind included); 16 tests.

(c) Hatcher et al. (1978): NRC Report NUREG-0373, wind tunnel tests, EOCR nuclear reactor, 3 releases (ground, roof, and stack), every 45°, 3 flows (unstable, neutral, stable); 72 tests.

(d) Start et al., (1980): NUREG CR-1395, full scale tests, same as Hatcher, emphasis on light wind, stable conditions.

Findings:

(1) Behavior of the five models is fairly similar.

(2) Models underpredicted wind tunnel observations for diagonal (45°) winds. Rooftop releases with 45° winds gave concentrations similar to ground-level releases with 0° winds.

(3) Models underpredicted during stable conditions, especially downwind.

(4) Models did best for low level sources beyond 3-5 H downwind.

(5) Full scale data had too much scatter, which masked differences between models.

(6) Wind tunnel (10 minute averaging time) measurements and model predictions were more conservative then full-scale measurements (60 minute averaging time).

Relevancy to AF Project:

The findings of this paper will provide insight into the performance of the dispersion enhancement approach for modeling different stabilities, wind directions, and release locations.

Comments:

(1) Not enough information is provided in this paper about the experiments to reproduce the modeled data, but plots of observed and predicted $\chi uH^2/Q$ vs. x/H for the different source locations and wind directions are provided.

(2) There is no discussion of wake kinematics, only a comparison of centerline concentrations and lateral and vertical plume half-widths.

(3) The wind tunnel averaging time should be considered in the model dose calculations.

(4) The finding of highest concentrations for 45° is consistent with Huber (1989): *Atm. Environ.*, **23**, 2109-2116.

Title: Parameters characterizing dispersion in the near wake of buildings.

Author: Fackrell, J.E.

Publication: J. Wind Engineering and Indus. Aero., 1984, Vol. 16, pp 97-118.

Findings:

(1) Downwind recirculating cavity length (λ) increases with increasing W/H and decreasing L/H.

(2) λ is longer without reattached shear layer on building roof.

(3) Hosker's cavity length equations overpredict observations because they are based on smooth approach flow. New formulas are proposed, but Hosker may be better for W/H > 5.

(a) Hosker $\lambda = 1.75\ (W/H)/[1.\ +\ 0.25\ (W/H)]$

(b) Fackrell $\lambda = 1.8\ W/H/[(L/H)^{0.3}(1.\ +\ 0.24\ W/H)]$

(4) Residence time (concentration decays by 1/e) in near wake increases with W/H but is independent of L/H.

Relevancy to AF Project:

The wind tunnel cavity length measurements and parameterizations are directly related to the needs of this project.

Comments:

(1) Both the Hosker and Fackrell cavity length formulas should be tested with the flow visualization data. Attention should be paid to whether the shear layer reattaches to building sides or roofs.

(2) Fackrell noted that aerosol tracer needed to be released upwind of building to fill wake laterally.

(3) Downwind sources had a significant concentration gradient close to the building, while upwind sources led to more uniform concentrations.

Title: Dispersion in the wake of a model industrial complex

Author: Hatcher, R.V., R.N. Meroney, J.A. Peterka and K. Kothari

Publication: U.S. NRC Report NUREG-0373, 1978

Findings:

A 1:200 scale model of the EOCR Reactor Complex in Idaho Falls was tested in a wind tunnel: three releases (ground-level next to building, vent from center of rooftop, and short stack on building), eight wind directions (every 45°), four stabilities (unstable, neutral, slightly stable, strongly stable). Main building was 37 m square and 23 m high and stack was 29 m tall. No momentum or buoyant plume rise.

(1) Aerodynamic turbulence dominates atmospheric turbulence in building wake and leads to greater dispersion than if no buildings.

(2) By $x/H_B = 8$, the increase in dispersion with downwind distance was independent of release position and building orientation.

(3) Atmospheric turbulence dominates by $x/H_B = 15$, and for $x/H_B > 15$ concentrations are independent of buildings.

(4) The effects of stratification in the wind tunnel are significant. Strongly stable stratification resulted in maximum concentrations within 100 m that were approximately double those during neutral conditions for ground level releases. Differences were smaller for elevated releases and for ground level releases further downwind.

(5) The concentration measurements indicated a longer wake downwind for flow perpendicular to the building. There were no specific measurements presented to quantify wake lengths.

(6) Concentrations for flow 45° to the building were about double concentrations during flow perpendicular to the building.

(7) For neutral ground level release, $\sigma_y \sim 2\sigma_z$ and $\sigma/H_B \propto (x/H_B)^{0.9}$.

(8) Ground level releases in wake have enhanced horizontal and vertical dispersion while elevated releases only enhance vertical dispersion.

Relevancy to AF Project:

The shape of the reactor facility is typical of buildings at industrial facilities. The effects of stratified flow and of wind direction can be studied.

Comments:

(1) Strongly stable flow results in significantly higher concentrations. Although quantified as "slight" in the paper, the differences can be a factor of two between maximum concentrations for a given release.

(2) The study covered both concentration fields and flow visualization, but there is no quantitative data presented on wake kinematics.

(3) Finding (8) is same conclusion reached in work of Alan Huber and William Snyder.

Title: The effects of buildings on local dispersion.

Author: Hosker, R.P. Jr.

Publication: Modeling the Urban Boundary Layer, 1987, American Meteorological Society, pp 95-160.

Findings:

This was a review paper that summarized the following findings on building clusters:

(1) Weak interaction, where upwind buildings affect flow near downwind buildings, can be treated as perturbation of isolated structure case. Strong interaction, where downwind buildings affect flow near upwind buildings, is much more complex. (Reference Britter and Hunt, 1979, *J. Indus. Aero.*, **4**, 165-182).

(2) Wake interference between structures occurs gradually as separation distance nears about 2.4 H for cubes; radius of influence near buildings with W/H > 3 is about 2.8 H displaced downwind by 1.6 H.

(3) Maximum jetting effect occurs with gap of 1.5 - 2.0 H.

(4) Maximum downwash for stacks on buildings with heights equal to 1.5 H occurs for centered stacks, minimum downwash for stacks on leeward edge. (Koga and Way, 1979, *Fifth International Wind Eng. Conf.*, Ft. Collins, 1003-1017).

(5) Rough estimates of flow and diffusion near a dominant structure can use techniques developed for isolated buildings.

(6) Numerical models might be developed with empirical parameterizations that insert wakes and vortices where known to occur.

Relevancy to AF Project:

The findings relating to wake interaction are relevant and offer hope for a successful model because of the dominant canyon buildings.

Comments:

(1) As a review paper, and not a detailed study, many of the conclusions are general. This is also a strength, since the work of many researchers have been synthesized into a few findings.

(2) The usefulness of this paper is in guiding whether nearby buildings are important. In particular, it appears that strong wake interactions and jetting are only likely to occur in the immediate vicinity of the canyon building because of the dense grid of piping and adjacent short buildings. The strength of these interactions needs to be quantified in the wind tunnel.

Title: The influence of building width and orientation on plume dispersion in the wake of a building.

Author: Huber, Alan H.

Publication: Atmospheric Environment, 1989, Vol 23, pp 2109-2116

Findings:

(1) For nonbuoyant sources centered at the leeward building edge of a squat building, the maximum downwind ground-level concentrations are higher by up to a factor of 3 for wind directions of 30°-45° to the building than perpendicular (0°) to the building.

(a) For a ground-level source and W/H=2 the increase was a factor of 3 at x = 3H and less than 1.5 at x = 10H.

(b) For an elevated source (z/H = 1.5) and W/H = 2 the increase was small at x = 3H but a factor of 2 at x = 10H for 45° - 60°.

(c) For W/H = 4 and W/H = 8 the ground level concentrations maintained the same behavior with changes in building orientation but the increases were smaller as W/H increased.

(2) Maximum downwind concentrations were reduced with increasing widths up to 10 H for perpendicular flow and a ground-level source. Beyond W = 10 H the side vortices had diminishing influence and concentrations increased. Beyond W = 20 H the maximum concentrations do not change with width.

(a) σ_y at x = 10 H incrased with width by a factor of 2 to W/H = 10, then decreased to W/H = 22.

(b) σ_z at x = 10 H increased by a factor of 1.5 to W/H = 10, then remained constant to W/H = 22.

(3) For ground level sources near the end of a W/H = 8 building, downwind concentrations at x = 10 H were twice those released near the center of the building for perpendicular (0°) winds. For 45° winds there was little change with release location. For sources released at a height of 1.5 H, plume downwash was reduced with placement near the end of a W/H = 2 building.

Relevancy to AF Project:

The canyon buildings are wide (W/H ~ 10) with potential nonbuoyant short stack or ground-level releases. Therefore, the wind tunnel observations of changes in dispersion with wind direction, release height, and source location are very relevant.

Comments:

(1) These experiments may be useful as an anchor to our study. It would be important to see if we can observe the same plume behavior. The findings of this paper are general and basic and should be able to be duplicated by any successful model.

(2) A deficiency of this paper is that no flow visualization or discussion of the wake kinematics are presented by Huber. We should carefully document the flow visualization with different widths and angles to more fully understand his results. Our study will also consider the additional effects of groups of buildings.

(3) We should obtain the Huber concentration data to test the model resulting from this project.

Title: Estimates of building surface concentrations from nearby point sources

Author: Wilson, D.J. and R.E. Britter

Publication: Atmospheric Environment, 1982, Vol. 16, pp. 2631-2646

Findings:

(1) The 3 cases for dispersion models are:

- (a) source and receptor in same unseparated flow
- (b) source and receptor in recirculation zone
- (c) source and/or receptor in unseparated flow but plume passes through recirculation zone.

(2) If plume centerline impinges on building surface the concentration will always be less than the maximum concentration on the undisturbed centerline.

(3) Close to the source on a building, the plume diffusion only depends on turbulence intensity and distance and not the building length scale.

(a) the building length scale

$R = H^{2/3}W^{1/3}$ for $W/H > 5$

$R = (HW)^{1/2}$ for $W/H \leq 5$

(b) in wake recirculation regions

$U_c i_c^2 \sim$ constant, where

U_c = mean wind speed in plume

i_c = turbulence intensity normal to plume

(4) Plume released in near wake recirculation zone will diffuse for $x \leq 1.7\ (HW)^{1/2}$ and will be uniformly mixed after $x > 1.7\ (HW)^{1/2}$.

(5) An upper bound on concentration on both the roof and within the downwind recirculation region is the global maximum concentration at the roof plane extending downwind.

Relevancy to AF Project:

The emphasis of this paper is recommending simple prediction methods for concentrations on building surfaces and in the downwind wake. The methods are based on physical principles and constants are determined from wind tunnel and full scale measurement programs. The general approach followed in this paper is a possible approach for the AF model.

Comments:

(1) This paper follows the pattern of others reviewed by dividing the downwash modeling problem into different parts based on source and receptor locations, and constructing different algorithms for each sub-problem.

(2) The modeling techniques in this paper are geared towards estimating the maximum expected concentrations (minimum dilution) and not the ensemble average concentration.

Title: Turbulent diffusion near buildings.

Author: Meroney, R. N.

Publication: Engineering Meteorology, 1982, Elsevier Scientific Publishing Co., pp 481-525.

Findings:

This was a review paper that presented the following general findings:

(1) Separation effects, secondary motions, and the resulting increased turbulence induced by buildings persist from 5-30 H downwind.

(2) Plumes above the roof separation region, but below the cavity separation streamline, usually remain aloft.

(3) A common modeling approach is to estimate a dimensionless concentration coefficient, K, as a function of distance, building shape, wind direction, and source location. ($\chi = KQ/uA$)

(4) Increased dispersion is a suggested technique for modeling groups of buildings or an industrial complex.

Relevancy to AF Project:

The findings would be useful for development of a generalized model structure.

Comments:

The paper offered further substantiation that the canyon building could be important to distances of at least 30 H. Otherwise much of the downwash modeling review was most relevant to adjacent building surfaces from vent or short stack releases. Peak to mean concentration ratios and dense gas dynamics were briefly discussed.

Title: Concentration fluctuations of a toxic material downwind of a building.

Author: Petersen, W.B. and A.H. Huber

Publication: EPA/A&WMA International Symposium on Measurement of Toxic and Related Air Pollutants, 1990, Raleigh, N.C.

Findings:

(1) A puff model can simulate the lateral concentration profile for a ground-level source downwind of a building.

(a) Tracer concentrations and video-image smoke (using laser and general light techniques from ceiling) with a W/H = 2 building were compared with INPUFF using a 4 puff per cycle model with superimposed random components. The cycle period was a function of wind speed and H.

(b) σ_x, σ_y, σ_z were enhanced in the puff model similarly to Huber and Snyder (1976), Third Symposium on Atmospheric Turbulence, Diffusion and Air Quality.

(c) The puff model could not match the peak concentrations. The data presented normalized the video data and model predictions to match the tracer concentrations at the centerline.

(d) The degree of concentration fluctuations is very sensitive to the choice of puff period and degree of randomness in the model.

Relevancy to AF Project:

This paper explores the feasibility of using a puff model, modified with a moving release location and enhanced puff diffusion coefficients, to simulate building downwash. The partial success of the comparisons makes it relevant to the model development phase of the project.

Comments:

(1) The puff model was tuned to match the peak concentrations and the puff cycle was chosen to match the video images. As the authors state, this is a preliminary investigation. The approach should be extended to see if the technique is more generally applicable to other source locations and building shapes.

(2) The sensitivity of choice of parameters should be explored.

(3) Thought should be given to whether a series of puffs between -0.8 H through 0 to + 0.8 H can more easily be simulated as a line source.

Title: Estimates of building surface concentrations from nearby point sources

Author: Wilson, D.J. and R.E. Britter

Publication: Atmospheric Environment, 1982, Vol. 16, pp. 2631-2646

Findings:

(1) The 3 cases for dispersion models are:

(a) source and receptor in same unseparated flow
(b) source and receptor in recirculation zone
(c) source and/or receptor in unseparated flow but plume passes through recirculation zone.

(2) If plume centerline impinges on building surface the concentration will always be less than the maximum concentration on the undisturbed centerline.

(3) Close to the source on a building, the plume diffusion only depends on turbulence intensity and distance and not the building length scale.

(a) the building length scale

$R = H^{2/3}W^{1/3}$ for W/H > 5

$R = (HW)^{1/2}$ for W/H $\leq$ 5

(b) in wake recirculation regions

$U_c i_c^2 \sim$ constant, where

U_c = mean wind speed in plume

i_c = turbulence intensity normal to plume

(4) Plume released in near wake recirculation zone will diffuse for $x \leq 1.7\ (HW)^{1/2}$ and will be uniformly mixed after $x > 1.7\ (HW)^{1/2}$.

(5) An upper bound on concentration on both the roof and within the downwind recirculation region is the global maximum concentration at the roof plane extending downwind.

Relevancy to AF Project:

The emphasis of this paper is recommending simple prediction methods for concentrations on building surfaces and in the downwind wake. The methods are based on physical principles and constants are determined from wind tunnel and full scale measurement programs. The general approach followed in this paper is a possible approach for the AF model.

Comments:

(1) This paper follows the pattern of others reviewed by dividing the downwash modeling problem into different parts based on source and receptor locations, and constructing different algorithms for each sub-problem.

(2) The modeling techniques in this paper are geared towards estimating the maximum expected concentrations (minimum dilution) and not the ensemble average concentration.

A-II

SUMMARY OF PAPERS ON EFFECTS OF OBSTACLES ON DENSE GAS PLUMES

Title: The Effects of Natural and Man-Made Obstacles on Heavy Gas Dispersion.

Author: P.W.M. Brighton

Publication: Safety and Reliability Directorate, United Kingdom Atomic Energy Authority, March 1989.

Brighton gives an extensive review of the literature and experiments done on heavy gas dispersion through obstacles.

Dimensional Analysis:

1.) Major variables in this study are release rate or size, initial density, wind speed, as well as subsidiary quantities such as aspect ratio (height-to-width ratio), temperature, and ground roughness.

2.) Windspeed is not uniquely defined since it is dependent upon height and atmospheric stability.

3.) Boussinesq approximation assumes that the density differences are important for buoyancy forces and not for inertial forces.

4.) For U/NH >> 1, where U = free-stream velocity, H = obstacle height, and

$$N = [-(g/\rho_a)(dr/dz)]^{1/2}$$

then the dense gas will flow over the obstacle similar to passive flow. When U/NH << 1, either part of the plume will be diverted around the obstacle or the whole plume will be diverted if H > h.

5.) Cloud Richardson # (Ri_c) is the ratio of gravitational potential energy in gas layer to its kinetic energy of advection.

6.) For $Ri_c H/h << 1$, mean flow is essentially passive because buoyancy forces are negligible compared to inertial.

7.) Cloud Richardson # also governs rate of top entrainment in plume. For $Ri_c <= 10^{-2}$ the process is passive. Richardson # rarely reaches values beyond unity.

Flow past isolated bluff-body structures:

1.) Length of recirculation region behind a cube varies from 6 to 13 times the height H of the obstacle.

2.) Beyond recirculation region at some distance downwind of

the building the mean velocity U(z) remains lower than its upwind value $U_o(z)$ at the same height by about 10% until x/H is greater than about 30.

3.) Distance from separation to reattachment decreases as the ratio of width to height (W/H) decreases.

Literature for 3-D steady plumes with obstacle downwind:

1.) Krogstad and Pettersen [3.9]. (Outline of paper done separately.)

2.) Kothari, Meroney, and Neff [3.10].

a.) Single source flow rate estimated at $113m^3/s$ at full scale. Scale at 1:250; 2 windspeeds; 21 obstacle configurations including flat ground with vertical cylinder main obstacle.

b.) Increases in concentration 300m downwind of up to 75% have been reported, particularly for the high wind speed. Is plume entering region of accelerated flow near the sides of the obstacle?

c.) It seems horseshoe vortex sweeps plume away from the obstacle preventing it from entering the recirculation wake. Precise mechanism is unclear and could just be the slowing of the plume as it is displaced around the obstacle.

Literature for 3-D instantaneous plumes with obstacle downwind:

1.) Dirkmaat [3.13]. Measurements made at unspecified locations.

2.) McQuaid and Roebuck [2.15]. Thorney Island trials 26 & 28, with obstacle downwind of the source.

a.) On building surface, peak concentrations decreased from 9% at ground-level to 3% at the top, to 1% on the roof.

Literature for 3-D steady plumes with obstacle upwind:

1.) Britter [2.7]. (Outline written separately.)

a.) The parameter b ranges from 0.216 to 0.809 in the experiments.

b.) Britter introduces a Richardson number defined by

$$R = g_o^1 q_o / U_w^3 H$$

which is a Richardson number based on the plate height. It ranges from $1.4x10^{-3}$ to 0.340 in these experiments. g_o is the gravitational acceleration multiplied by the relative cloud density at the source

$$g\frac{\rho_o-\rho_a}{\rho_a}$$

and q_o is the volume flux.

i.) For $R < 4x10^{-3}$, mixing in recirculating wake observed to give uniform distribution.

ii.) For $R > 4x10^{-2}$ the plume spread laterally outside the recirculating wake, and for $R > 0.2$ the spread was greater than the obstacle width. Britter concluded that this was caused by a synergistic interaction of the horseshoe vortex and the lateral gravity spreading.

2.) Thorney Island Trials 27 & 29. Obstacle upwind of the source.

Literature on 3-D source impinging onto a 2-D fence:

1.) Britter [2.7].

a.) Concentration in lee of fence seems to be highly dependent upon H/h and not on $U_w/(g_o q_o/w_{nf})^{1/3}$, where w_{nf} is the plume width without the fence.

b.) Pattern of mixing in the lee is 2-D within bounds of the widened plume.

2.) Davies & Singh [3.14]. (Comparison to Thorney Island Trials 20, 21, 22.) Blocking of dense gas onto the barrier and a reflected wave of the first arrival of gravity current.

3.) Mcquaid & Roebuck [2.15] (Comparison to Thorney Island Trial 21). Peak concentrations show sharp reduction just downstream of fence by a factor of 3.

4.) Konig [4.5]. Studied heavy gas dispersion with nine idealized obstacle configurations:

a.) For obstacles 3 + 4, a tall and short channel parallel to the wind direction with width $2Q_{o1/3}$ and source along centerline:

i.) The channel strongly inhibits lateral spreading, making centerline conc. 3 times greater than flat-terrain concentrations.

ii.) Konig's instantaneous results agree well with Brighton's reference model for instantaneous 2-D releases for the first 3 measuring postions. Further away concentrations drop by a factor of two (This could be due to gas overflowing sides of channel as Konig observed but did not quantify.)

iii.) Konig's continuous results in the high channel flow can be compared to 2-D steady flat-terrain reference model.

b.) Obstacle 5 was a semi-circular fence downwind of the source, which compares well with Thorney Island Trial 20.

c.) Obstacle 6 consisted of two intersecting channels at right-angles; source at the intersection.

i.) Presence of intersection creates additional turbulence to significantly influence dilution rates in the streamwise channel.

ii.) Concentrations in the transverse channel are low.

d.) Obstacle 8 was a ditch transverse from the plume. Enhanced dilution is observed with the ditch than with flat-ground.

e.) Obstacle 9 was a high-sided channel at 45 degrees to the wind direction.

Riethmuller's experiments on street-liked obstacles:

a.) Riethmuller performed experiments using many obstacles in an industrial setting. On the whole the obstacles created a net diluting effect.

b.) Obstacles generate turbulent wakes which may enhance dispersion downwind.

Thorney Island Phase 3 trials:

a.) These experiments simulated continuous heavy gas spills from a storage tank into a bund (fence enclosing storage tank.).

b.) Release created a "pool" of gas spreading well upwind gas was then drawn quickly over the downwind fence.

c.) Qualitative behavior of the gas in the bund can be compared to Britter's [2.7] results of releases in the wake of a bluff body. Unfortunately, there is little quantitative data from within the bund.

d.) The effect of the plume hitting the downwind fence can be compared with 2-D flow onto the fence:

i.) In 2-D plume interaction the plume Richardson number is important as well as ratio of the plume depth and fence height. (Fig. 4.1 of Brighton)

ii.) Britter [2.7] found that when a heavy gas plume passes over a fence higher than plume height, there is passive mixing in the lee up to the full height of the obstacle, providing an important diluting mechanism.

e.) The bund has a diluting effect of 3 by itself (trial 38) when compared to trials without the bund, and a diluting effect of 4-6 when combined with the effect of the container (trials 45-47).

f.) Holdup of the gas in the bund lowers initial conc. for subsequent downwind dispersion and creates a lower effective release rate.

Kothari & Meroney [4.8]:

a.) Experimented with fences and rows of vortex generators surrounding heavy-gas source. Continuation of [3.10].

b.) 126 runs made using 4 windspeeds, 3 source flow rates, 2 obstacle types, 2 obstacle heights, and 3 obstacle layouts.

c.) Vortex generators were triangular plates angled 30 degrees from hoizontal, 19m at base, and height refers to apex above ground.

d.) For almost all cases high obstacles (10m) have greater dilution than low obstacles (5m).

e.) Diluting effect of vortex generators less than that of fence.

Riethmuller - Experiments on Barrier-like obstacles [3.12].

a.) 13 of his tests involved cuboid blocks arranged in rows transverse to wind flow.

i.) In some cases odd number of blocks was used such that the plume would impinge on the block, and

when an even number was used the plume would go thru a gap. Size of gap made little difference.

b.) For 3-block configuration, dilution mainly effected by large obstacles and not by terrain effects (roughness elements).

c.) With 3-blocks at center of site area, combined dilution effect of roughness and large blocks greater than product of those two effects separately.

d.) With 2 blocks, downwind of obstacles roughness does have additional diluting effect.

e.) In some experiments, presence of obstacles increases concentrations, by a factor of up to 3.9 for site model or 1.9 for roughness array. No discussion of these results.

f.) However, Riethmuller made no velocity measurements or visual observations.

Brighton's conclusions and observations:

1.) Since heavy gases remain near the ground, plume depth would be comparable to height of roughness elements. There is little info even on passive flow characteristics in these regions. Array of roughness elements is the type of obstacle most in need of investigation.

2.) Britter and Snyder [2.10] yielded small changes using a ramp with a height that would have caused large perturbations in the plume if it were a fence.

3.) There is no experimental data on a valley configuration or a cutting with sloping sides. This scenario could be potentially hazardous, since lateral plume spreading would be hampered by the force of gravity acting down on the slopes.

Title: Overall properties of the heavy gas clouds in the Thorney Island Phase II Trials.

Author: Brighton, P.W.M., Prince, A.J.

Publication: J. Hazardous Materials, 16, 103-138.

This paper discusses some of the dense-gas cloud characteristics of the Thorney Island Phase II trials plus three flat-ground trials. The obstacles in the phase II trials were a cubical obstruction, impermeable semi-circular barrier, and permeable semi-circular barrier.

Background Information:

a.) Phase I are trials 7-19.

b.) Flat-ground trials discussed in this paper are trials 5,6, and 34.

c.) Trials with cubical obstruction with side of 9m are trials 26-29.

d.) Trials with semi-circular barrier are trials 20-25.

e.) Authors took area-averaged concentrations, where ground-level concentrations are averaged over the horizontal extent. For barrier cases, upwind and downwind areas are separated in area-averaging. Extensive data shown on many figures of concentration vs. tau.

f.) Phase I area-averaged concentrations showed a smooth decrease of concentration with time:

   1.) At small times, there was a small dilution rate indicative of edge entrainment.

   2.) At larger times, concentrations decrease more rapidly due to top entrainment.

Results:

a.) Of the flat ground trials analyzed, trials 6 and 34 were consistent with the behavior of phase I trials.

b.) Buildings:

   1.) Building has no effect on initial gravity spreading behavior up to the time the cloud reaches the obstacle.

   2.) There is an order of magnitude reduction in conc.

on front face of bldg, which is probably due to existence of horseshoe vortex wrapped around the upwind faces of the bldg, bringing upper air down towards the faces of the bldg and outwards at ground-level, opposing the approach of heavy gas at ground-level.

3.) The near-wake did not show any striking differences compared to overall cloud average concentration. This opposes Krogstad and Pettersen, who found concentrations in near wake had been reduced to similar scale as in upwind.

c.) Semi-circular impermeable barrier:

1.) Gravity-spreading rate unaffected by barrier prior to cloud reaching the barrier, but translational advection speed is considerably smaller than on flat-ground.

2.) The heavy gas splashes over the fence; a reflected wave is observed; part of cloud is trapped upwind of barrier in virtual stagnant region, with wind carrying cloud slowly over the top.

3.) Downwind, the cloud is much deeper and dilute than in flat-ground cases, and it spreads at a slower rate because of its depleted buoyancy content.

4.) Leading part of cloud is advected downwind at same speed as in flat-ground. However, in the wake of the obstacle the slower windspeed according to the authors must be counterbalanced by a greater cloud height.

5.) For trial 20 with a low Richardson number of 500:

i.) Upwind conc. remained high up to tau = 200, while the downwind conc. are an order of magnitude lower.

ii.) After tau = 200, conc. converge towards the flat-ground results.

iii.) For high Richardson #'s, there are similar concentration profiles with high upwind concentrations and low downwind concentrations that eventually approach flat-ground levels at later times.

6.) At later times, the mean conc. downwind is similar to those in flat-ground conditions.

7.) Figures of cloud height vs. tau show that cloud

height is fairly constant upwind at around the height of the barrier (5m), but downwind it rapidly becomes greater than 10m.

8.) Some problems; could not estimate how rapid material is transferred from upwind to downwind parts of the cloud; cloud area could not be determined, nor could cloud height be effectively determined downwind.

d.) Semi-circular permeable barrier:

1.) For the permeable fence, effects are less severe than impermeable fence.

2.) Area-averaged concentrations are similar to the flat-ground tests.

3.) Cloud depth is increased within the obstacle, and downwind, average cloud height is about the same as in the flat-ground trials.

4.) Speed of the front is about the same as flat-ground, but the rear of the cloud is reduced in speed, elongating the cloud, and making it grow more slowly than in flat-ground.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow characteristics of the Thorney Island Phase II gas cloud trials, which are full-scale field trials of dense gas dispersion around obstacles.

Comments:

Data presented in many figures of area-averaged concentration vs. tau, a nondimensionalized time.

Cloud heights vs. tau are also shown in many figures, although reliability of downwind cloud height is questionable in some cases.

Title: Experiments on some effects of obstacles on dense-gas dispersion.

Author: R.E. Britter

Publication: SRD R 407, Safety and Reliability Directorate, United Kingdom Atomic Energy Authority, Wigshaw Lane, Culceth, Warrington, WA3 4NE, United Kingdom, 1989.

A series of wind tunnel tests were made of a dense gas source interacting with various obstacles. Three steady flows and one unsteady flow were discussed in detail in this report. They were:

1.) Impingement of a 2-D plume onto a 2-D obstacle. (2-D solid fences of heights 0.5, 1, 2, 5, 10, and 20 cm where positioned 1.5 m downstream of a CO_2 line source normal to the flow.) 3 source flow rates. 3 free stream velocities. 54 runs.

2.) Interaction of a dense plume from an area source with a 2-D fence. (A 10cm x 10cm area source was situated at the same position as the line source.) 34 runs.

3.) Area source just behind a 3-D obstacle. (A 5cm x 5cm area source was placed in the immediate lee of a flat square metal plate (5x5, 10x10, 15x15 cm^2) normal to the flow.) 4 stream velocities. 3 source flow rates. 3 obstacles and 1 no-obstacle run. 48 runs.

4.) 3-D instantaneous release in the near wake of a 3-D obstacle (15cm x 15cm). 5 different densities. 1 run without obstacle. 10 runs.

Observations of the 2-D plume impinging onto the 2-D obstacle:

1.) When $h_{0.5}/H >= 2$, there is less than 20% reduction in max concentration in immediate lee caused by insertion of fence, where,

$h_{0.5}$ = height where plume concentration is half of ground-level concentration.

H = obstacle height.

2.) To dilute the concentration in immediate lee by a factor of 2, $H/h_{0.5} >= 1.5$.

Observations of dense gas plume from area source impinging onto 2-D fence:

1.) The plume increases in width before surmounting obstacle.

2.) The width increase is larger for higher obstacles and for more stable plumes.

3.) If the obstacle was large compared to plume depth, the mixing and dilution in the immediate lee is as if the flow was effectively passive.

4.) If plume depth was large compared to obstacle height ($h_{0.5} > H$), then there hardly is any influence of obstacle on ground-level concentration.

5.) Similar results might be expected if the obstacle were a 2-D step.

Observations of area source behind a 3-D obstacle:

1.) Decrease in velocity produces larger ground-level conc. at x = 1h (h = plate linear dimension).

2.) With Q, U, and h fixed, ground-level conc. increases with increase in density of plume material.

3.) At x = 2h, outside the recirculating region, the flow appears essentially passive, although there may be dense-plume effects downstream when

$$\frac{g^{1}Q}{U^{3}h} \geq 0.01$$

where

$$g^{1} = g(\rho_2 - \rho_1)/\rho_1$$

4.) Simple analytical model developed by Brighton[1] is in broad agreement with quantitative results.

1 Brighton, P.W.M., Heavy-gas dispersion from sources inside buildings or in their wakes, I Chem E Symposium on Refinement of Estimates of the Consequences of Heavy Toxic Vapour Releases, Manchester, UK, 8 January 1986.

Observations on 3-D instantaneous source in wake of 3-D obstacle.

1.) For an obstacle with

the immediate wake appears passive when

$$H/V^{1/3}=1.5$$

$$[\frac{g_o^{\prime}V_o^{1/3}}{U_o^2}]^{1/2}<1.5$$

where V_o = volume of instantaneous release.

2.) Influence of the obstacle may be neglected when

$$[\frac{g_o^{\prime}V_o^{1/3}}{U_o^2}]^{1/2}>3.0$$

3.) Observations were restricted to within five obstacle dimensions of the obstacle.

Relevancy to the U.S. Air Force Project:

The findings in this paper will help to describe the flow of dense gases past a fence-like object and the flow of a dense-gas source in the immediate wake of an obstacle such as a building.

Comments:

Very little discussion and comparison between the results and the model developed by Brighton for the continuous area source behind a 3-D obstacle.

Title: Fluid Modeling of Dense Gas Dispersion Over a Ramp.

Author: R.E. Britter and W.H. Snyder

Publication: Journal of Hazard. Mat., 18, 1988, 37-67.

Flow of a dense (CO_2) and neutral (air) gas plume was investigated in a wind tunnel, over both flat terrain and over a ramp.

Experimental conditions:

1.) Data taken at free-stream wind velocities of 1 and 4 m/s in a turbulent boundary layer.

2.) A ramp was placed 1800 mm downwind of the source with a slope of 13.2 degrees from horizontal.

3.) The ramp was then moved closer to exactly 600 mm from the source with a slope of 13.6 degrees.

4.) Experiments over flat terrain were also made, totalling to six distinct runs.

Observations over flat terrain:

1.) Ground-level concentrations between neutral and dense plumes were remarkably similar downstream from the source.

2.) The lateral concentration profile for a neutral plume was Gaussian, while for a dense plume it was very flat-topped with sharp tails.

3.) Concerning vertical concentration profiles, the neutral plume had a higher profile than the dense plume, and its profile was in the form of

$$C/C_{max} = \exp[-Az^n] \quad where\ n \approx 1.5$$

while the dense plume had a vertical profile of

$$C/C_{max} = \exp[-z/\overline{z}] \quad : \overline{z} = centroid\ of\ distribution.$$

Observations over the ramp:

1.) The ramp created 30% and 40% reduction in the ground-level concentration of dense plumes at 1800 mm and 600 1mm downstream of the source respectively. Results were

similar for neutral plumes.

2.) However, the mechanism for concentration reduction for the 2 types of plumes was proposed to be different:

a.) For the neutral plume, the increased dilution occurred a very short distance up the slope and continued as the plume traveled over the ramp.

b.) For the dense plume, the primary mechanism is the increased travel time, which allowed for greater lateral spreading. Most of the dilution occurred as the plume traveled to the top of the ramp, and very little had occurred at the ramp base.

c.) The main effect of the ramp on the dense plume was to alter the velocity field field in which the plume was developing in rather than a direct influence of the ramp on the plume.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow of dense gases over a ramp in flat terrain.

Title: An experimental study of two-dimensional atmospheric gas dispersion near two objects.

Author: Kim, S., Brandt, H., White, B.R.

Publication: Boundary-Layer Meteorology, 52, 1-16, 1990.

The paper discusses two-dimensional heavy gas dispersion over two square objects, one behind the other, in a wind-tunnel experiment.

Laboratory conditions:

a.) Argon gas was used as dense gas with specific gravity of 1.5 compared to air.

b.) Two continuous source flow rates: 3.55 and 4.93 m^3/min per lateral meter.

c.) 2-D flow field in fully turbulent flow: roughness Reynolds # > 2.5. (Re_z = 5.05 in runs.)

d.) Approach velocity = 1.637 m/s at h = 0.076 m.

e.) Obstacles were 2 square objects with a height (H) and length of 76 mm. First object is one obstacle height behind the source and second object is one obstacle height behind the first object.

Results:

a.) Gas conc. below 1H and in front of first object is 4 to 5 times higher than in any other region, so that the gas cloud resides between the source and the first object. The authors suggest that the approach flow moves over the dense gas cloud instead of being mixed with the gas cloud.

b.) In the region between the buildings, gas is well-mixed below one object height, then the concentration increases from 1.0H to 1.25H, and then the conc. decreases at higher heights.

c.) At one object height behind the second object, which is within the recirculation zone, we see the same qualitative pattern as in the region between the buildings. There is no gravitational settlement observed in the two recirculation zones.

d.) Gas was dispersed no higher than 2H near the objects, and no higher than 3.5H at 9H downstream.

e.) Measured concentrations compare well with numerically computed concentrations based on Kim (1988).

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow of dense gases over fence obstacles.

Comments:

a.) Concentration data shown in figures for various positions upstream and downstream, including points between the 2 buildings.

b.) Two datasets collected. Authors did not make a run without any obstacles.

Title: Accelerated dilution of liquefied natural gas plumes with fences and vortex generators.

Author: Kothari, K.M., & Meroney, R.N.

Publication: Gas Research Institute Report GRI 81/0074.

Paper discusses dilution effects of fences and vortex generators on liquefied natural gas plumes.

Laboratory conditions:

a.) 3 simulated LNG boiloff rates (20,30,40 m^3/min)

b.) 4 windspeeds (4,7,9,12 m/s at 10m height).

c.) 6 configurations of fences or vortex generators with 2 heights for each device.

d.) Scale of 1:250.

e.) Total of 138 tests performed.

f.) Both vortex generators, which were equilateral triangles, and fences had equivalent dimensions of 75x75x5 m, 150x150x5 m, 75x75x10 m, and 150x150x10 m.

g.) Mixture of ethane(3%) and carbon dioxide (97%) for a combined specific gravity of 1.5 was used as the model gas.

h.) LNG boiloff area simulated for diameter of 75m.

i.) Ground-level concentration measurements taken.

j.) Equal values of the Froude number for the model and real-life conditions were maintained by adjusting reference wind speed.

Results:

a.) $C_{fence}/C_{no\ fence}$ increases with higher boil-off rate under identical wind speed.

b.) LNG plume gets wider as windspeed decreases.

c.) Without any obstacles, intermediate windspeed (7m/sec) gave maximum concentrations.

d.) Concentrations were always smaller with fence or vortex generator present than without any obstacles.

e.) When either a fence or a vortex generator was present, lower wind speed resulted in higher ground concentration.

f.) In most cases, two rows of fences or vortex generators created slightly smaller concentrations than a single row of fences or vortex generators.

g.) The closer the fence or vortex generator is to the source, the greater the diluting effect.

h.) The higher the obstructing device, the lower the concentration.

Conclusions:

a.) The fence or vortex generator creates higher turbulence which spreads the LNG plume and allows for quicker plume dilution.

b.) Solid fences gave higher dilution than vortex generators, possibly because vortex generators produced a vortex pair which suppressed vertical mixing and reduced turbulence intensity.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow of dense gases around obstacles such as fences and vortex generators.

Comments:

Data presented in figures and tables, making it very accessible. Contour plots are also provided.

Title: LNG Plume Interaction with Surface Obstacles.

Author: K.M. Kothari, R.N. Meroney, D.E. Neff.

Publication: Gas Research Institute Report, GRI 80/0095.

A wind-tunnel test on a 1:250 scale model using LNG and neutral density plumes was performed, with a variety of obstacle configurations both upwind and downwind of the source.

Experimental conditions:

a.) Wind-tunnel tests were performed to simulate these live-scale conditions:

i.) LNG boiloff rate of $30m^3$/min, and an equivalent flow rate for a neutral plume.

ii.) LNG boiloff area with diameter of 75m.

iii.) LNG storage tanks with diameter and height of 50m.

iv.) 2 windspeeds: 4m/s and 7m/s.

b.) 21 different sets of obstacle configurations.

i.) Cubic building with length of 18.75m.

ii.) Tree line with height of 7.5m and porosity of 30%.

c.) Ground-level concentration (mean and peak) data taken at downwind distances.

Results:

a.) Highest concentration observed without obstacles, with the higher wind speed producing the maximum concentration.

b.) With an obstacle, the lower speed resulted in higher concentrations.

c.) Mean concentration with the neutral plume was 3 to 5 times smaller in magnitude than LNG plume.

d.) With cylindrical tank upstream of spill area, initial dilution at 100m downwind was 2 to 3 times smaller with LNG plume than with neutral plume, suggesting that even with the excess turbulence created by the tank, there is less entrainment of air into the dense LNG plume than with the neutral plume.

e.) Highest plume dilution was observed with the cylindrical tank upstream and closest to the spill area.

f.) Measured LNG plume concentration usually has maximum off the centerline, particularly when obstacle is downwind, suggesting three possible reasons:

i.) Higher turbulence in wake creates higher entrainment and thus lower conc. in wake region.

ii.) Presence of horseshoe vortices deflect lower conc. air downward along centerline.

iii.) Plume is laterally displaced by the obstacle.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow characteristics of dense plume dispersion in comparison with neutral plume dispersion with obstacles both upwind and downwind of the source.

Comments:

Data presented in tabular and graph form; furthermore, concentration contours shown on many figures, providing access to their experimental data.

Title: Windtunnel modelling of a release of a heavy gas near a building.

Author: P.A. Krogstad and R.M. Pettersen

Publication: Atmospheric Environment, vol. 20, 867-878, 1986.

A heavy gas (freon 12) is continuously released upstream of a rectangular block (one corresponding to a 2-story bldg and another to a 4-story bldg). Tests were done with the model axis either perpendicular to the flow or along the flow direction, at distances of
14, 24, and 44 cm downstream from the source. Concentration measurements were collected on all the exposed sides of the model.

General Observations:

1.) Model sizes were LxBxH = 15x6x3 cm and 30x12x6 cm, which at a scale of 1:200 corresponds to a two-story and four-story building.

2.) Model release rate was determined to be 5 liter/min at a wind speed of 0.72 m/s (measured 5cm above tunnel floor). This was to match full-scale release of 20 cubic meter/s at a wind speed of 4.4 m/s measured at 10 m.

3.) Twelve distinct test runs.

Observations with the model perpendicular to the flow (W/H = 5):

1.) Highest concentration levels were found on upstream wall near the floor and along the sides.

2.) Concentration levels on the rear wall were lower and constant which typically suggests a separation region with strong mixing.

3.) On the roof, concentration levels in the forward part part matched values on the front wall, and rear part matched values on the rear wall.

Observations with the model axis along the flow direction (W/H = 2):

1.) Maximum concentration is about the same as in the above case.

2.) High concentration levels are exclusively found near the floor.

3.) Back wall concentrations are also constant but higher than in the above case.

Conclusions:

1.) An unobstructed gas cloud behaves like a passive passive contaminant for x(sqrt(U/V)) > 8. (V = release rate)

2.) Concentration levels on the model surface are very low no matter where the model is positioned along the center line.

3.) Surface concentration level depends upon the model-height to cloud-height ratio with high ratios giving low concentrations.

4.) Wide models give higher surface concentration levels.

Relevancy to the U.S. Air Force Project:

The results of this paper will help describe surface concentrations of a building downwind of a continuous dense gas release.

Comments:

The gas was released from a hemisphere with D = 5.7 cm. However, most of the gas was emitted from the sides where the static pressure is lowest, creating a kidney-shaped cloud with low gas concentrations along the center axis (non-uniform cloud concentration along axis perpendicular to flow).

Title: Wind Tunnel Modeling of Density Current Interaction with Surface Obstacles.

Author: Klaus Marotzke

Publication: Meeting of the CEC - Project BA at TNO in Apeldoorn, The Netherlands, Sept. 29-30, 1988.

Marotzke performed wind-tunnel experiments using a dense gas (not stated) on various surface obstacles, in part to repeat some of Konig's findings with his experiments. The ambient conditions such as surface roughness and profile-exponent were the same as in Konig's experiments. All concentration measurements were taken at ground-level along the center axis of the wind direction.

Results:

a.) For instantaneous and continuous releases with no obstacles present, Marotzke shows good agreement with Konig's ground-level concentrations downwind of the source. (Shown on figures.).

b.) Single side wall parallel to wind direction: Instantaneous and continuous releases show deviation from unobtructed case above, with concentrations higher at a given x.

c.) Source in middle of street canyon parallel to wind direction:

1.) Three instantaneous runs with varying canyon height show that concentrations are significantly larger than unobstructed case for a given x downwind. The highest height showed the highest concentrations, probably because the cloud was prevented from overflowing the walls.

2.) Three continuous experiments were performed using two different heights and three different channel lengths. All heights appeared to be infinite to the cloud.

a.) With an infinite height, reducing the width by a factor of 1.3 resulted in a corresponding increase in concentration.

b.) The concentrations are well above the unobstructed case even with a wide canyon.

d.) Semi-circular wall downstream. Instantaneous and continuous experiments both show a substantial decrease in ground-level concentrations downwind of obstacle. Figures also show large concentration fluctuation at the wall that Marotzke does not discuss in detail.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow of dense gas dispersion on various obstacles downwind of the source in comparison with flow without obstacles.

Comments:

Marotzke does not give specific numbers on wind velocity or obstacle dimensions.

Title: Some Effects of Obstructions on the Dispersion of Heavy Gas Clouds.

Author: J. McQuaid

Publication: Symposium on Refinement of Estimates of the Consequences of Heavy Toxic Vapour Release, Manchester, UK, 8 Jan 1986. I. Chem. E. North Western Branch Papers 1986 No. 1.

McQuaid discusses the effects of certain obstacles on heavy gas dispersion, making reference to the Thorney Island Phase II trials. Comparison trials without obstacles were based on the equality of the initial Richardson #.

Major Obstacles:

1.) Semi-circular impermeable fence with height 5m and situated 50m from spill point. Purpose was to study the effects of partial and complete blocking.

2.) Permeable screen 10m high to simulate a wall of trees in a semi-circular arc of 50m.

3.) A cubical building (dimensions unknown) placed 50m downwind in three trials and 20m upwind in one trial.

Results:

a.) Semi-circular impermeable fence:

1.) Cloud front impacted fence and splashed over, being elevated 2-3 times the height of the fence. A reflected wave traveled back from the fence, while the main body of the cloud was held up by the fence and was gradually carried over the fence in separated flow.

2.) During the initial splash, the vertical downwind concentration profile is uniform up to fence height and then increases to double the ground-level concentration at 2 fence heights.

3.) Compared to a similar run without a fence, the concentration distribution is considerably lower (by a factor of 3) at all points downwind.

b.) Permeable screens:

1.) Main difference between permeable and impermeable screen was that there was no splashing of the cloud

front or a reflection from the screens.

2.) Passage of cloud was delayed in the wake of screens when compared to tests without screens. This effect is present at all heights up to screen height.

3.) Downwind of screen, concentration is significantly lower than no-screen case but not as extreme as in the impermeable case.

c.) Building:

1.) Building creates overall diluting effect downwind of the bldg when compared to no obstacle, but not as much as in the two previous cases.

2.) Presence of gas was of short duration on top face of building, corresponding to the splash of the cloud front.

3.) Main body of cloud, with a depth of half the height of the building, was carried around the building.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the flow of dense gas dispersion on various obstacles downwind of the source, in comparison with flow without obstacles.

Title: Vapour barrier assessment programme for delaying and diluting heavier-than-air HF vapour clouds -- a wind tunnel modelling evaluation.

Author: R.L. Petersen and R. Diener

Publication: J. Loss Prev. Process Ind., 3, 187-196.

Simulated HF releases in a moderate to heavily obstructed industrial plant-like setting with various obstacles downwind of the release.

Laboratory Conditions:

a.) Similarity requirements: same velocity ratio; same density ratio; same densimetric Froude No.; ensure fully turbulent boundary layer; same Richardson No.; maintain Peclet/Richardson no. ratio > 0.5, where

$$Pe^*/Re^* = U^{*3}/g^1\beta$$

b.) Two site configurations: 'moderately obstructed' and 'heavily obstructed' industrial plant-like sites.

c.) Homogeneous roughness lengths, z_o = 3 and 50 cm (installed upwind and downwind).

d.) Stability: D and F

e.) Wind speed at 10m, 3 and 5 m/s.

f.) Downwind distances, x: 100 to 3000 m

g.) HF mass release rates: 6.3 and 25.3 kg/sec

h.) Initial relative density of 1.19 and 1.33

i.) Release orientation: horizontal, vertical, and angled.

j.) Release duration: 60 to 480 sec.

k.) Obstacles:
Barrier 1: Wall 10m high and 50m long, 30m from source.
Barrier 2: 3 fences with staggered openings.
Barrier 3: Semi-circular wall (50m radius).
Barrier 4: Two angled walls converging on downwind side.
Barrier 5: Fence system with vertical motion.
Box 8: 10m high 40x50m box with opening bottom

sidewalls.
Box 10: Box with 20m high, 40% porous screen surrounding.

1.) Over 200 simulations performed, including runs without any barriers or obstacles for the two generic industrial plants.

Results:

a.) For no barriers, concentration reduction factors approach unity at both close to and far from the release with a peak in the middle.

b.) For barriers:

1.) The 'heavily obstructed' site had larger conc. reduction factors than the 'moderately obstructed' site.

2.) For 'moderately obstructed' sites:

a.) Barrier 3 (semi-circular fence) had highest reduction factor of 6 at 100m compared to others which had a factor of 3 or less.

b.) At 500m, reduction factor for all barriers was 1.5.

c.) At 2000m, reduction factors approached unity.

3.) For 'heavily obstructed' sites:

a.) Barriers 2 and 4 had a reduction factor of 9 at 100m.

b.) Barrier 5 (device to induce vertical motion) had lowest reduction factors.

c.) At 500m and 1000m, reduction factors approach unity for all barriers.

4.) Barriers did not appear to significantly increase cloud arrival times.

c.) Box-like obstacles:

1.) Box 8 did not significantly reduce conc. both in near and far-field.

2.) For box 10, near-field conc. reduction factors range from 5 to 9. There was also a far-field reduction of 2 to 4, unlike any of the other

obstacles.

3.) Far-field reduction is due to ability of vapor box to retain a portion of release, reducing rate of gas release. This will last as long as box volume is large enough to contain volume of gas.

4.) Increasing box height lowered reduction factor.

5.) Large boxes had smaller reduction factors than smaller boxes.

6.) Most effective box was 10m closed box with 15 or 20 m porous screen (box 10).

7.) For the box, concentration reduction factors increased with decreasing wind speed, increasing stability (D to F), increasing release rate, shorter release durations, horizontal releases (vs. vertical), and grassland vs. higher surface roughness surroundings.

8.) Boxes did not significantly increase cloud arrival times in 'moderately obstructed' settings.

Relevancy to U.S. Air Force Project:

The results of this paper will help describe the dispersion of HF releases around a variety of obstacles in an industrial plant-like setting.

Comments:

Concentration reduction factors and cloud arrival time differences are shown in various figures for all the major obstacles discussed in the paper.

Authors did not specify gas used to simulate a HF gas release.